Evaluation of Underperforming Rooftop PV Plants in India – Moving from kW to kWh

Part IV: Evaluation of 10 Rooftop PV Plants in Surat

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List of abbreviations

AC	Alternating Current	**LTA**	Lender´s Technical Advisor
BOM	Bill of Materials	**LV**	Low Voltage
BOS	Balance of System	**MPP**	Maximum Power Point
CAPEX	Capital Expenditures	**MPPT**	Maximum Power Point Tracker
COD	Commercial Operation Date	**MV**	Middle Voltage
DC	Direct Current	**MWp**	Megawatt peak
DIF	Diffuse Horizontal Irradiance [Wh/m²]	**OE**	Owner´s Engineer
EL	Electroluminescence	**OPEX**	Operating Expense
EOW	End of Warranty	**O&M**	Operations and Maintenance
EPC	Engineering Procurement and Construction	**PAC**	Provisional Acceptance Commissioning
FAC	Final Acceptance Commissioning	**PCU**	Power Central Unit
FC	Financial Close	**PID**	Potential Induced Degradation
GHI	Global horizontal irradiation [Wh/m²]	**POA**	Plane of the Array
Isc	Short-circuit current	**PPA**	Power Purchase Agreement
IR	Infrared	**PR**	Performance Ratio
IV	Irradiation / Voltage	**PV**	Photovoltaic
KVA	Kilo-Volt-Ampere	**SPD**	Solar Project Developer
LCOE	Levelized Cost of Energy	**STC**	Standard Test Conditions
LID	Light Induced Degradation	**Voc**	Open circuit voltage

1. Executive Summary

The Government of India is aiming for an exponential increase in the installation of renewable energy systems in the country including 100 GW capacity of solar power by 2022 out of which 40 GW is targeted on rooftops. While the efforts are being directed towards substantially increasing the rooftop solar capacity, it is imperative to ensure that these systems perform with high yields. The rooftop solar team at Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) has analyzed the specific yields of various systems and has found that many systems are performing sub-optimally. The technical advisory company PI Photovoltaik-Institut Berlin AG (PI Berlin) has been contracted by GIZ to identify the causes of sub-optimal performance in 10 pre-selected rooftop PV plants, quantify those in terms of contribution to loss in generation and propose cost-optimal solutions to address the quality issues. This contract is part of the project Indo-German Solar Energy Partnership – Photovoltaic Rooftop Systems (IGSP-PVRT) and is financed by the German Federal Ministry for Economic Cooperation and Development and implemented by GIZ in partnership with the Ministry of New and Renewable Energy (MNRE)

In cooperation with GIZ and PI Berlin's local partner GSES[1], and thanks to the support of private developers, SECI[2] and the Distribution Companies, the access to the 10 roofs was secured. The results of the evaluation of each of the PV plants presented in this study show that the low performance of the inspected PV plants is caused by a combination of (i) limited O&M, (ii) near shadings, (iii) high module degradation rates and (iv) module product defects. Higher module degradation rates and limited O&M (heavy soiling) stand out in this group, followed by near shading and mechanical damage of the modules. According to the observations and measurements conducted by PI Berlin during the site assessments, the identified findings can contribute individually to losses at the system level between 8% and 15%. The absence of O&M contracts stating (a) clear procedures for preventive and corrective maintenance, (b) reaction times and (c) contractual availability values, is a factor that also contributes decisively to lowering the PV plant's output.

One of the goals of the project is that future O&M contractors and developers can benefit from the knowledge and conclusions drawn from the evaluation of the PV plants presented in this study. In this sense, PI Berlin suggests 5 concrete revamping and repowering measures that, depending on the state of each PV plant, may lead to a performance boost between 5% and 25%. PI Berlin has identified 10 prevention mechanisms to ensure the revenues and reduce the exposure to adverse technical, management, or environmental risks. These technical and commercial de-risking measures, for the next generation projects, are based on international standards, best practices and PI Berlin's criteria beyond the norms.

[1] Global Sustainable Energy Solutions India
[2] Solar Energy Council of India

2. Introduction and Background

The Government of India is aiming for an exponential increase in the installation of renewable energy systems in the country including 100 GW capacity of solar power by 2022 out of which 40 GW is targeted on rooftops. With this in mind, India's cumulative solar rooftop photovoltaic installations reached ca. 4.4 GW at the end of 2019 [Mercom]. While the efforts are being directed towards substantially increasing the rooftop solar capacity, it is imperative to ensure that these systems perform with high yields. The rooftop solar team at Gesellschaft für Internationale Zusammenarbeit (GIZ) has analyzed the specific yields of various systems and has found that many systems are performing sub-optimally. The technical advisory company PI Photovoltaik-Institut Berlin AG (PI Berlin) has been contracted by GIZ to identify the causes of sub-optimal performance, quantify those in terms of contribution to loss in generation and propose cost-optimal solutions to fix the quality issues.

Under the Indo-German technical cooperation, the Government of Germany is cooperating with India and has commissioned a project through the German Climate Technology Initiative (DKTI). The project Indo-German Solar Energy Partnership – Photovoltaic Rooftop Systems (IGSP-PVRT) is financed by the German Federal Ministry for Economic Cooperation and Development and implemented by GIZ in partnership with the Ministry of New and Renewable Energy (MNRE). The project aims to support MNRE in achieving the 40 GW targets announced for rooftop solar power plants under the National Solar Mission.

The objective set by the GIZ for this project is to conduct a quality evaluation of 40 selected underperforming rooftop solar PV systems across India and quantify the issues leading to sub-optimal performance and suggest specific measures along with cost benefit analysis to increase their performance. The results will lead to synthesizing a solution, potentially in the form of business models for O&M companies. This report summarizes the results of the assessment of the fourth set of 10 rooftop PV plants, located in Surat, in the West Indian state of Gujarat.

3. About PI Berlin

The Photovoltaik-Institut Berlin is a leading technical advisor, risk manager and quality assurance provider for PV power plants and equipment. With its experienced team of researchers, scientists and engineers, PI Berlin offers a wide range of design, testing and evaluation services with a focus on the risk management and quality assurance of PV equipment and complex PV power plants. PI Berlin has already supported 11 GW of PV power plants worldwide, with over 245 audits conducted on over 115 manufacturers producing more than 67 GW of PV equipment annually.

PI Berlin has an IEC 17025 accredited test laboratory at its Berlin location for evaluating the performance, reliability and durability of solar modules. Another test laboratory is located in Suzhou, China. Modules are tested according to strict criteria that meet or exceed IEC standards.

4. Description of the Inspection Methodology

PI Berlin has conducted the present study in three steps which will be described in the present chapter.

Preparation Phase

The preparation phase is mainly focused on selecting and securing the access to the roofs. The selection criteria were agreed with GIZ and can be detailed as follows:

1. An equal number of roofs from all available DISCOM´s shall be selected
2. PV plants with different nominal capacities shall be selected (50 kW to 1000 kW)
3. PV plants with low and very low specific yields are preferred. At least one plant with average or above average yield will be selected to be used as a benchmark
4. Plants with consistent data during the last 12 months will be selected.

A list of required technical documents was created and sent to the rooftop owners in order to conduct some intelligence on the PV plant´s history and health. The documents were categorized according to its relevance and applicability. Additionally, in preparation of the second visit, PI Berlin arranged a SOP[3] to introduce the expected on-site activities in order to expedite the access. In parallel, GIZ approached the DISCOMs and introduced PI Berlin and its local partner GSES to the representatives in charge. The DISCOMS enabled finally the access to the rooftop owners. Based on the meeting outcomes with the owners and the completeness of the shared documentation, 10 roofs were selected for conducting the present study.

Data Acquisition

Ahead of each visit, the available documentation was reviewed in order to maximize the efficiency during the site inspection. PI Berlin and GSES conducted the site visits spending one day per site. The site inspections focused primarily on aspects that have direct impact on the performance, such as (i) module cleaning, (ii) PV module degradation, (iii) shading situation and (iv) inverter unavailability or poor maintenance. Safety issues, without a direct impact on the performance, were also documented.

PI Berlin’s evaluation covered 7 main topics as shown in the following scheme:

[3] Standard Operating Procedure

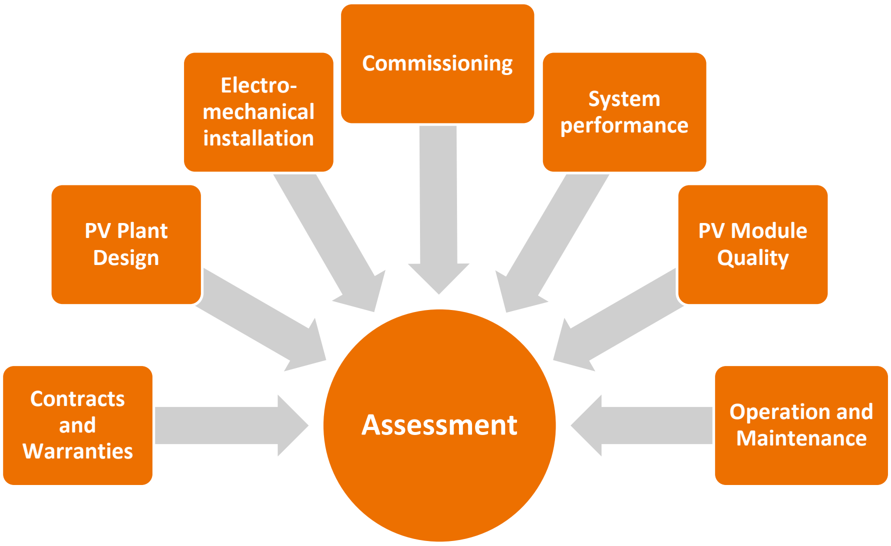

Figure 1: Scope of the evaluation

In the first topic **Contracts and Warranties**, the legal and commercial scenario of the PV project were evaluated from a technical perspective. EPC and O&M contracts along with the performance warranties were analyzed. The suitability of the selected products for a specific location together with the technical design were evaluated in the second topic, **PV Plant Design**. The quality of the **Electromechanical Installation** of the PV plant is the third topic and was covered on site. The fourth topic **Commissioning** covered the review of the tests conducted after the handover. In the fifth topic **System Performance,** the performance indicators of each plant were analyzed. The topic **PV Module Quality** assessed the status of the PV modules on site by conducting a visual inspection and measurements using special equipment. Finally, the last topic **Operation and Maintenance** evaluated the preventive and corrective measures carried out by the O&M team. The described scope was applied separately to each of the 10 PV plants using the checklist shown in Annex III.

Post-processing and Reporting

The information gathered onsite was post-processed and combined with the results of the documentation reviewed ahead of the visit. Each of the findings responsible for performance drop has been, as far as possible, coupled to an estimated energy loss and feasible mitigation measures. The final statements of PI Berlin in regards to the quantification of the impact of the identified findings, are based on (i) PI Berlin's long-term experience in the PV sector, (ii) on-site data acquisition and (iii) simulations using PVsyst software. The results achieved by PI Berlin will provide answers to the following questions:

1. Which findings arise more often and which have the highest impact on the performance?
2. Which retrofitting solutions can be implemented to boost the energy production of the inspected PV plants?
3. Which mechanisms are needed to avoid underperformance and to ensure the revenues in the next generation projects?

5. List of the Selected Sites: Surat

Surat is a port city situated on the banks of the Tapi River. With its Tropical climate, Surat provides a unique scenario for the evaluation of system exposed to challenging weather conditions. The selected sites under the scope of the project are shown in the following table.

Table 2: List and location of the selected sites

PV Plant	Installed capacity (kWp)	Average specific yield since COD
IV.1	80	738 kWh/kWp
IV.2	80	874 kWh/kWp
IV.3	50	941 kWh/kWp
IV.4	20	781 kWh/kWp
IV.5	80	1046 kWh/kWp
IV.6	40	1012 kWh/kWp
IV.7	20	1041 kWh/kWp
IV.8	80	1048 kWh/kWp
IV.9	100	1065 kWh/kWp
IV.10	100	1074 kWh/kWp

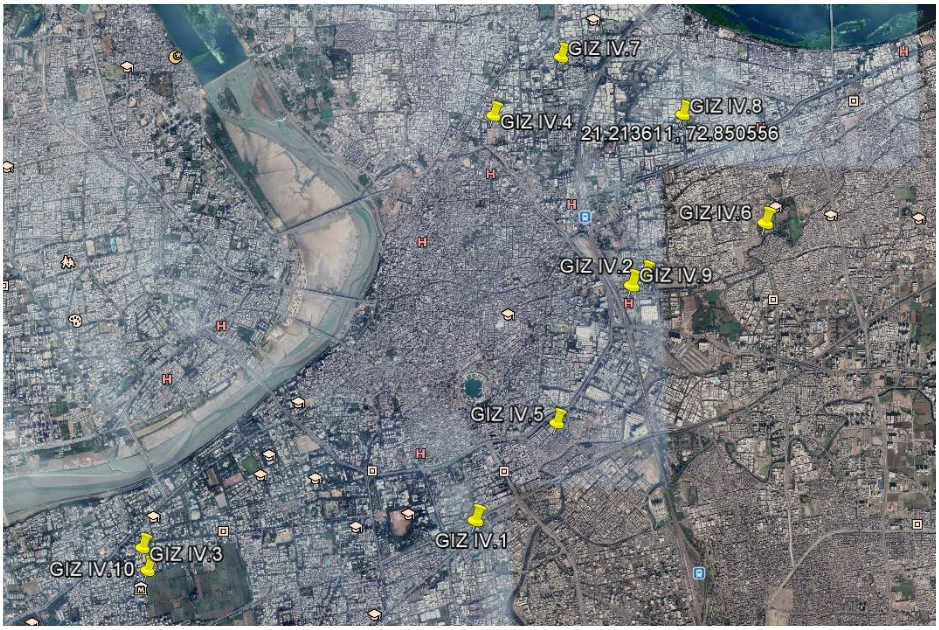

Figure 2: Sites within Surat area

Climate characteristics: Surat

Surat lies on average 7 m above sea level. According to Köppen-Geiger, Surat is classified as tropical (Aw), characterized by an obvious dry season. The summers have a fair amount of rainfall while winters nearly zero. The average annual rainfall is 1192 mm, with most precipitations in July (ca. 446 mm), and the driest period is December to April. May is the warmest month, with an average of 31.3 °C and December the coldest with an average temperature of 22.2 °C [source: climate-data.org].

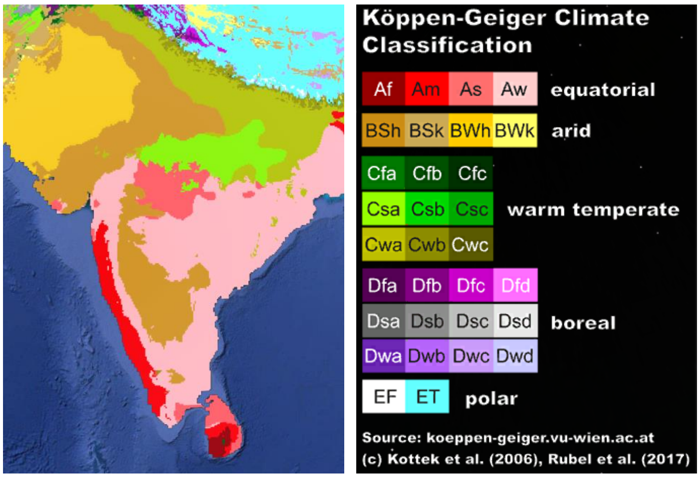

Figure 3: Köppen-Geiger climate classification map for India (1980-2016) [17]

The average Global Horizontal Irradiation (GHI) in the region is 1973 kWh/m² [source: SolarGIS].

Figure 4: Global horizontal irradiation map of India [source: SolarGIS] (left); Global horizontal irradiation map of Surat, Gujarat [source: SolarGIS]

6. Technical Background

This chapter serves as a guide for the better understanding of some of the module failures mentioned in the present study.

6. 1. Potential-Induced Degradation

The phenomenon of Potential-Induced Degradation (PID) is based on a power loss degradation caused by a negative potential of the solar cells towards earth, which leads to an accumulation of Na^+ located in the glass and migrating into the solar cells damaging the p-n junction responsible for the electron flow [14]. The degree of affection is highly dependent on the level of the potential (voltage stress). The first bibliographic references relate to the investigations carried out by Hoffman and Ross (JPL) in 1978 ("Impact of voltage-biased humidity exposure of solar modules on long-term stability") in which this physical effect was internationally presented for the first time. The PID effect was associated in the past principally to back contact cell technology, TCO corrosion in thin film modules and processes based upon band silicon. In recent years, the PID effect has also been linked to silicon technology; thus, this phenomenon has become more and more relevant due to the enormous amount of solar facilities built with this technology.

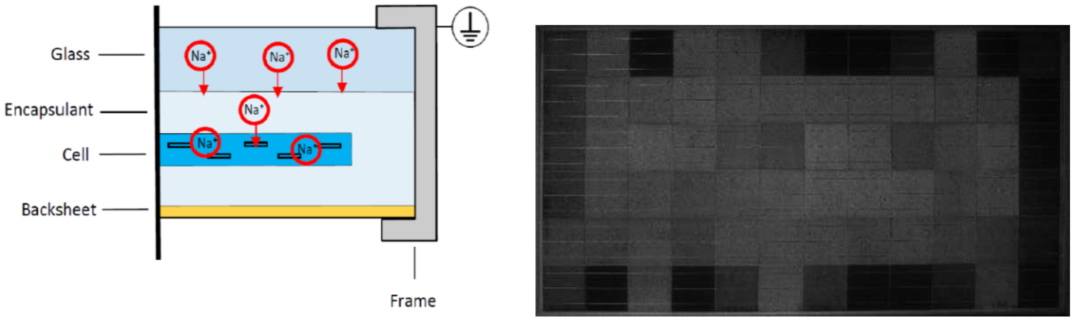

Figure 5: p-n junction damage (left) and typical PID pattern (right) [source: PI Berlin]

The necessary conditions for the appearance of PID in the field can be summarized as follows:

- High system voltage (has increased in the last years in order to minimize transport losses in the string)
- High relative humidity and high temperature
- Certain combination of materials (glass, encapsulate material, etc.)

The degree of PID of the PV modules decreases towards the positive pole, with the first modules of the negative pole being usually the most affected with power drops up to 95% in cases of advanced PID.

6. 2. Snail Trails

It is defined as a grey/black discoloration of the silver paste of the front metallization of screen-printed solar cells. In the PV module the effect looks like a snail trail on the front glass of the module and is visible to the human eye. The discoloration occurs along invisible cell cracks. The discoloration typically occurs 3 months to 1 year after installation of the PV modules. During the summer and in hot climates snail trails occur faster [9]. The area of the snail trail discoloration along the silver finger of the front side cell metallization shows nanometer-sized silver particles in the EVA above the silver finger. These silver particles cause the discoloration [5], [14]. The snail trails appear typically as branched trails across the cells and are a clear sign of hidden cell damages [15], [18].

Figure 6: PV module showing snail trails [source: PI Berlin]

6. 3. Hot Spots

A hot spot is defined as a localized region in a PV module whose operating temperature is very high in comparison with its surroundings. This can occur when a cell generates less current than the rest of cells connected in series as a result of partial shading, cell damage, mismatching or interconnection failure. As a result, the defective cell is reverse biased and behaves like a load that dissipates the power generated by the rest of the cells in the form of heat [14]. The protection against hot spots is also well-known and consists of connecting a bypass diode, with reverse polarity, in parallel with a group of cells, typically 12 or 18 for crystalline silicon modules. Thus, the defective cell is reverse biased to a point that causes the forward conduction of the bypass diode, which almost short circuits the group of cells and ensures that, in the worst case, the aforementioned cell dissipates nearly the power generated by the remaining cells in the group [12]. Hot spots present a potential risk of irreversible damage for PV modules. They can cause, for example, tedlar delamination, glass breakage, loss of electrical insulation or even fire [14].

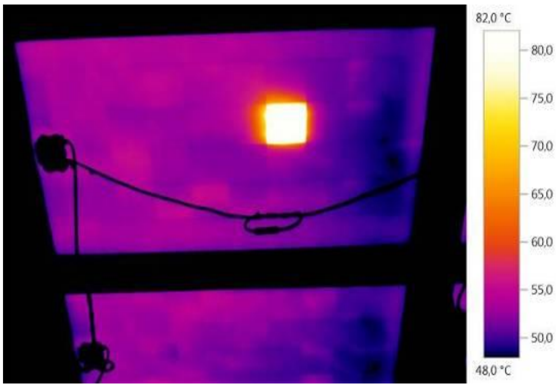

Figure 7: PV Module affected by a hot spot [source: PI Berlin]

6. 4. Inactive Cell Strings

In parallel to a certain number of solar cells, bypass diodes are integrated into the PV module. These bypass diodes reduce the power loss caused by partial shading on the PV module. Besides the power loss, the diode avoids the reverse biasing of single solar cells higher than the allowed cell reverse bias voltage of the solar cells. If a cell is reversed with a higher voltage than it is designed for, the cell may create hot spots that may cause browning, burn marks or, in the worst case, fire. Typically, Schottky diodes are used as bypass diodes in PV modules. Schottky diodes are very susceptible to static high voltage discharges and mechanical stress. So they should be handled with care and human contact without grounding should be avoided [14]. Consequently, many bypass diode failures may occur. But it is difficult to find them because they only attract attention when the PV modules have severe mismatch in the individual IV characteristic of single cells, e.g. caused by shading or disconnected parts of a cell due to cell cracks [9].

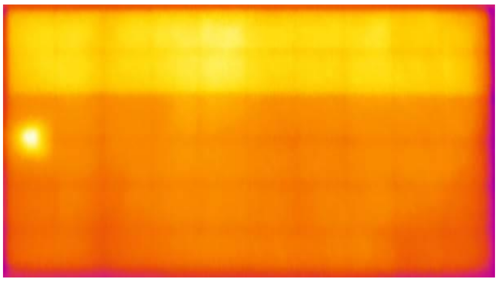

Figure 8: PV Module with an inactive cell string [source: PI Berlin]

6. 5. Cell Breakage and Microcracks

Photovoltaic cells are made of silicon. This makes the cells very fragile. Cell cracks are cracks in the silicon substrate of the photovoltaic cells that often cannot be seen by the naked eye. Cell cracks can form in different lengths and orientations in a solar cell. The wafer slicing, cell production, stringing, the embedding process during the production of the solar cell and module, transport, handling and installation are all sources of cell cracks in the photovoltaic cells [5],[14]. The cracks and microcracks can be detected easily with electroluminescence technique as shown in the picture below.

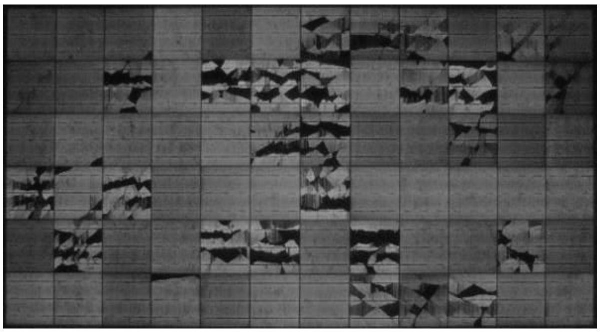

Figure 9: PV Module showing cracks and microcracks [source: PI Berlin]

The associated power losses to the aforementioned phenomenon will depend on the size and depth of the crack, while the crack propagation is purely influenced by the site conditions (for instance, wind, temperature and snow).

7. Results of the Analysis

The following section summarizes the outcomes of the investigations conducted by PI Berlin on the 10 rooftop PV plants.

1

PV plant: ***IV.1***

Nominal capacity: ***80 kWp***

Average specific yield since COD (March 2014): ***738 kWh/kWp***

Abstract: *The Plant is affected by soiling (pollution and bird drops), inconsistent installation angles and near shadings. Furthermore, the module power performance is significantly lower than the expected values, likely due to a combination of installation and product failures modes (mainly PID and cracks). It is recommended to (i) increase cleaning frequency, (ii) irradiation sensor re-installation, (iii) homogenize module tilt angles, (iv) install an anti-PID box to stop PID degradation and (v) conduct string reengineering based on cracks and power classes. The estimated production boost expected by the retrofitting actions lies between 16-25%.*

PV Plant's health

Main Findings

- Heavy soiling caused by nearby industrial area and bird droppings have been detected.
- Due to the limited access to the roof, it is likely that the modules suffered from mechanical stress during transport, handling and installation.
- A few installation failures were discovered, such as scratches in the module backsheet, disregard of bending radius and cables in contact with sharp edges and exposed to UV load.
- The irradiation sensor on the plane (GTI) was poorly installed and at a different angle than expected.
- Through IR inspection, several modules with warm cells, inactive strings and shading induced hotspots were detected.

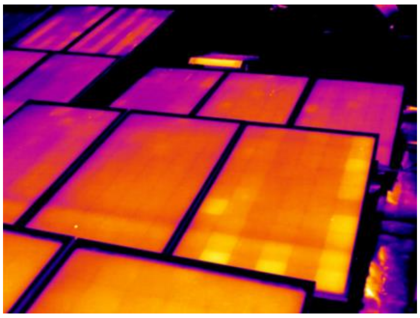

Figure 10: PID affected module

- Product failures at module level were detected, such as open J-boxes or hot cables at the J-box from poor soldering or clamping.

Impact on Performance

- The losses due to near shadings (trees) could represent 7% less irradiance loss, based on a representative simulation.
- The inconsistency in the module tilt angle, combined with the deviation from the optimum azimuth, lead to ca. 3% yield loss from the optimum orientation.
- An average soiling factor of 6% was determined from IV curve measurements of sample modules, before and after cleaning.

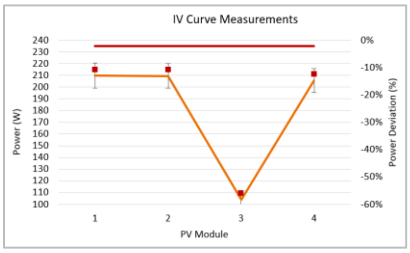

Figure 12: On-site power measurements

- The PID effect could be responsible for more than 20% of performance losses on system level. Individual module measurements showed nominal power drops higher than 55% (104W) in the modules with negative polarity.

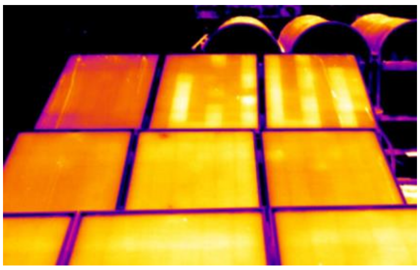

Figure 13: Modules in short circuit (IR)

- Spikes against birds shall be installed at the upper edge of the modules to reduce bird drops (soiling).

Proposed Solutions

- The tilt and shading angles throughout the plant shall be homogenized.
- Likewise, the irradiation sensor should be properly reinstalled to ensure accurate readings.
- Increasing the albedo from 0.2 to 0.5 by painting the rooftop surface in white and adding reflective materials to the rear side of the modules, leads to an increase of the irradiation on POA of at least 1.8%.
- Modules with heavy cracks shall be grouped in the same string or at least assigned to one MPPT. The grouping will be conducted based on infrared inspection with high irradiation levels and after cleaning.
- Furthermore, PV modules showing power drops above the warranty conditions shall be replaced. If the replacement is not possible, the modules shall be regrouped in power classes within the same string and assigned to individual MPPT.
- An anti-PID measure, such as anti-PID box, shall be implemented in order to stop or reverse the degradation.

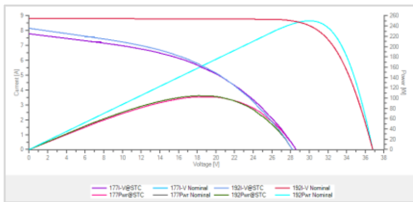

Figure 14: Module IV-curve with PID

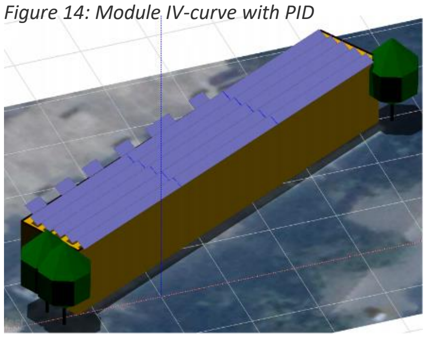

Figure 15: 3D model of the system

Estimated energy boost after conducting the suggested retrofitting actions: 16% to 25%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.4 ₹/Wp, 0.2 ₹/Wp/a

Picture Gallery


Figure 16: General view of the system


Figure 17: Preparation for soiling measurements

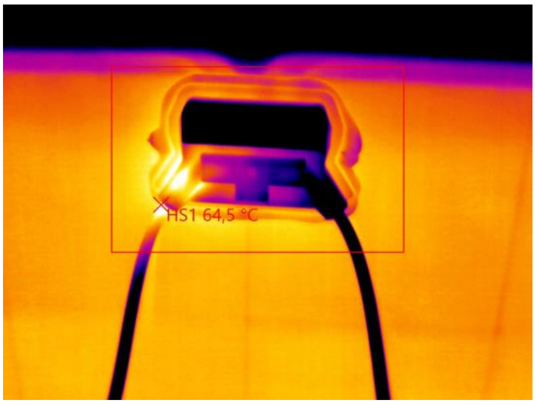

Figure 18: J-boxes with hot joints (soldering/clamping)


Figure 19: Cable management (damaged/bending)


Figure 20: Snail trails (microcracks)

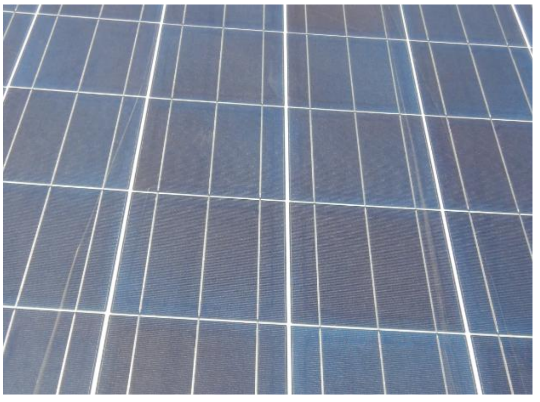
Figure 21: Cell "framing" or discoloration effect


Figure 22: Improper installation of reference Si-sensor

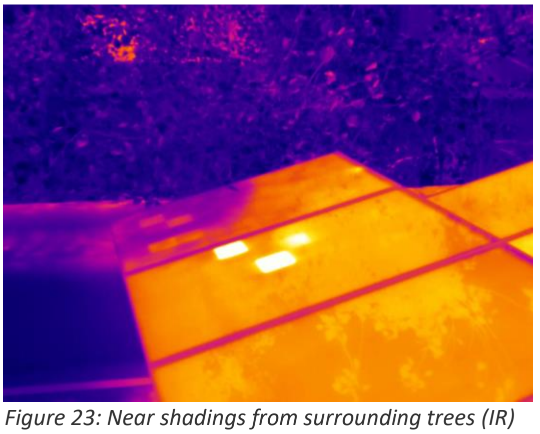
Figure 23: Near shadings from surrounding trees (IR)

2

PV plant: ***IV.2***

Nominal capacity: ***80 kWp***

Average specific yield since COD (March 2014): ***874 kWh/kWp***

Abstract*: The PV plant is affected by significant near shadings caused by surrounding trees in the South and East part of the system and advanced PID degradation. Furthermore, the modules showed substantial underperformance and affection by shunts. It is recommended to (i) replace missing fastening screws, (ii) conduct a string reengineering with individual MPPT assignments, based on IR inspection, (iii) replacement of modules exceeding the manufacturer's guaranteed performance drop and (iv) replacement of modules with defective J-boxes. The estimated production boost caused by the retrofitting actions lies between 17-25%.*

PV Plant's health

Main Findings

- The system is not properly grounded.
- The screws of the fastening clamps are not tightened correctly.

Figure 24: Screws of the fastening clamps

- The angle of the irradiation sensor deviates slightly from the module angle.
- Some parts of the cables are exposed to UV radiation. Pipes conveying cables are open and some parts have already broken.

Figure 25: Broken cable ducts

- The modules present different types of J-box failure types, e.g., overheated, open or missing lid.
- String cables damaged by, or in contact with sharp edges were spotted.
- Modules with broken front glass were found.
- Cable ties broke, hence the module cables and connectors are loosely hanging.

Impact on Performance

- Soiling losses were determined based on the measurements on-site to be 1.2%, on average.
- Several modules with snail trails were found during the visual inspection.

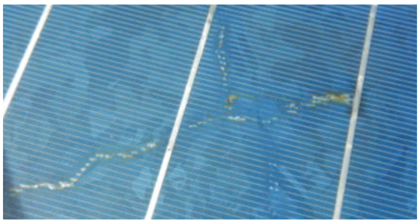

Figure 26: Modules with snail trails

- Near shading is caused by nearby trees.

Figure 27: Near shading by trees

- PID leads to a performance loss of as high as 29% at the module level based on the measurements conducted on site. The degradation is in a fairly advanced stage. The impact at the system level is estimated to be around 10%.

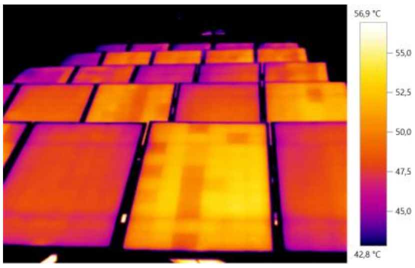

Figure 28: Modules with PID

- Several hot spots were discovered in the plant.

Proposed Solutions

- The missing fastening screws should be replaced and all screws should be checked.
- An anti-PID measure, such as anti-PID box, should be implemented in order to stop or reverse the degradation.
- The trees surrounding the system should be trimmed if allowed. Otherwise, a restringing of the modules should be conducted in the following way: modules with similar shading conditions should be installed in the same string or at least assigned to one MPPT.
- PV modules showing power drops above the warranty conditions should be replaced. If the replacement is not possible, the modules should be regrouped in power classes within the same string and assigned to individual MPPT.

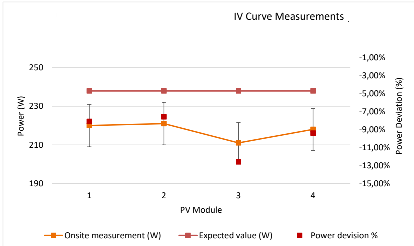

Figure 29: Onsite power measurements

- Modules with any defect on the J-box should be immediate replaced (safety, operation and reliability issues).
- The simulation of the system showed a shading loss of 6.9%.

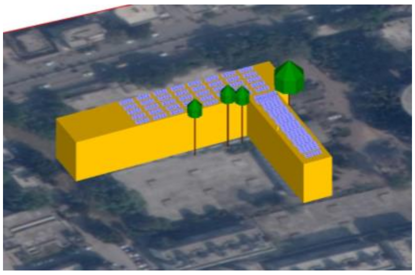

Figure 30: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 17% to 25%

Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.9 ₹/Wp, 0.1 ₹/Wp/a

Picture Gallery


Figure 31: Non-functional grounding


Figure 32: Shading by objects in the building


Figure 33: Broken J-Box lid

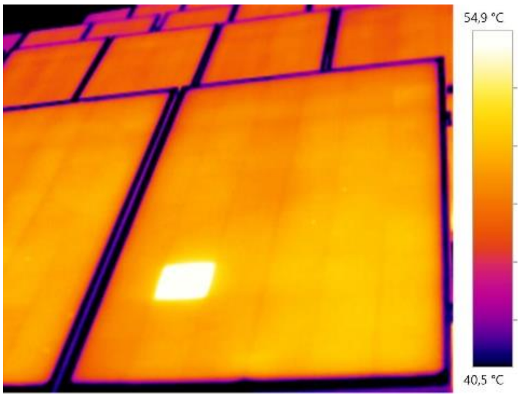

Figure 34: Module with warm cells

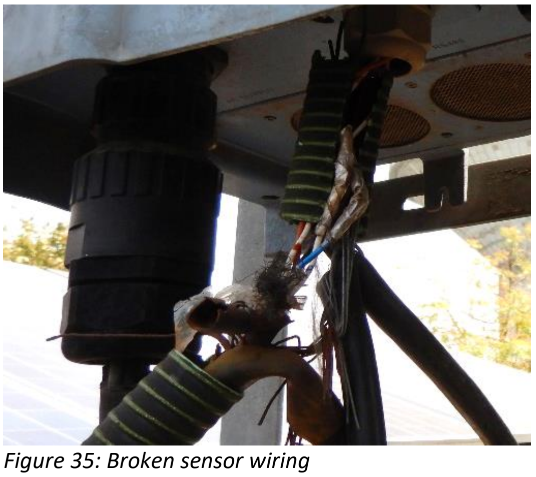
Figure 35: Broken sensor wiring


Figure 36: Broken modules


Figure 37: General overview of the system


Figure 38: Radiation sensor in POA

3

PV plant: ***IV.3***

Nominal capacity: ***50 kWp***

Average specific yield since COD (March 2014): ***941 kWh/kWp***

Abstract*: The PV plant is affected by PID problems. The electroluminescence investigation showed some micro cracks with isolated cell areas. Furthermore, the DC wiring shows several damages. It is recommended to (i) stabilize the shaky mounting structure, (ii) implement anti-PID solutions, (iii) replace modules exceeding the manufacturer's guaranteed performance drop and (iv) replace modules with defective J-boxes. The estimated production boost caused by the retrofitting actions lies between 6-20%.*

PV Plant's health

Main Findings

- The outer modules are installed on a very shaky mounting structure.
- The modules present different types of J-box failure types, e.g., overheated, open or missing lid.

Figure 39: Open J-Box lid

- The cables of the irradiation sensor are not installed correctly.
- Some parts of the cables are exposed to UV radiation. Some cable ducts are brittle and some have already broken.

Figure 40: Broken cable ducts

- The modules present different types of J-box failure types, e.g., overheated, open or missing lid.
- String cables damaged by, or in contact with sharp edges were spotted.
- Cable ties broke, hence the module cables and connectors are loosely hanging.
- The connectors of the string cables on the inverters have fallen off.
- Some cables are only connected with duct tape.

Impact on Performance

- Based on the measurements on-site, the soiling losses were determined to be 4.2%, on average.
- The thermographic examination showed some overheated plugs.

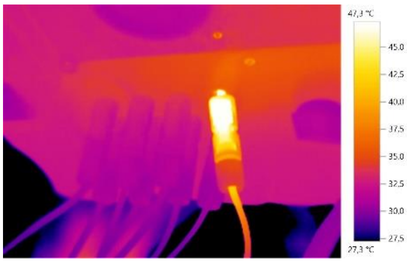

Figure 41: Overheated plugs

- First signs of a possible PID problem were recognized.

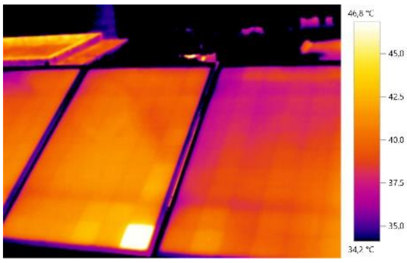

Figure 42: PID affected modules

- The electroluminescence investigation confirmed the PID suspicion and showed further damage such as micro cracks and isolated parts.

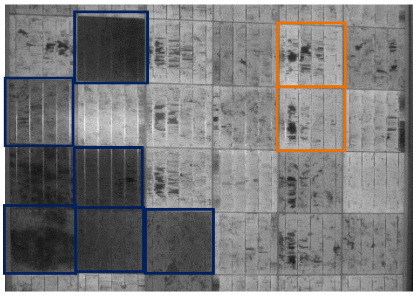

Figure 43: PID affected module sample

- Several hot spots were discovered in the plant.

Proposed Solutions

- The mounting structure shall be retrofitted / strengthened.
- An anti-PID measure, such as anti-PID box, should be implemented in order to stop or reverse the degradation.
- All DC wiring should be properly maintained.
- PV modules showing power drops above the warranty conditions should be replaced.

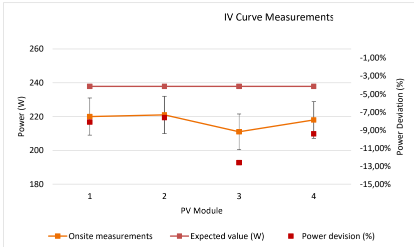

Figure 44: Onsite power measurements

- Modules with any defect on the J-box should be immediate replaced (safety, operation and reliability issues).
- The simulation of the system showed a shading loss of 1.3%.

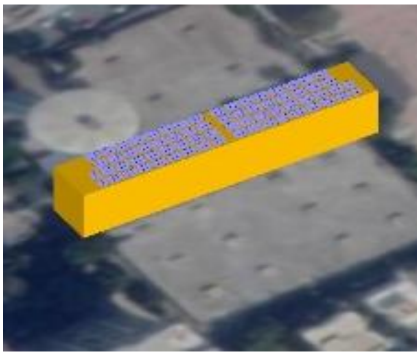

Figure 45: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 6% to 20%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.1 ₹/Wp, 0.3 ₹/Wp/a

Picture Gallery


Figure 46: Open J-box


Figure 47: Cables in contact with sharp edges


Figure 48: Broken J-box lid

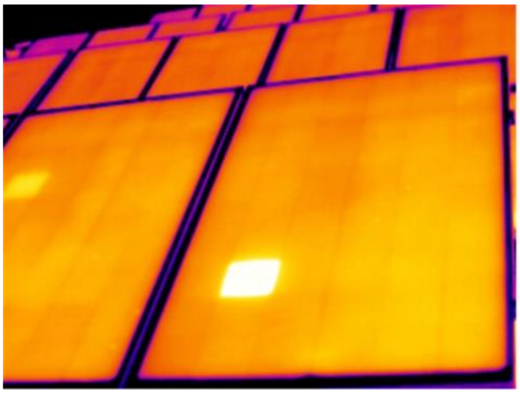
Figure 49: Hot spot


Figure 50: Loose hanging cables


Figure 51: Cables connected with duct tape


Figure 52: General overview


Figure 53: Broken MC connector

4

PV plant: ***IV.4***

Nominal capacity: ***20 kWp***

Average specific yield since COD (March 2014): ***781 kWh/kWp***

Abstract*: The Plant was installed facing East, reducing almost by a quarter the overall energy generation. It is significantly affected by near shadings and soiling. Additionally, various modules and installation defects were discovered through visual and infrared inspection. In general, module power performance is significantly lower than the expected values (due to PID effect). It is recommended to (i) replace modules with exposed J-box, (ii) increase cleaning frequency, (iii) re-install the irradiation sensor, (IV) implement an anti-PID box solution. The estimated production boost expected by the retrofitting actions lies between 16-25%.*

PV Plant's health

Main Findings

- The plant was installed facing East. If the system was designed to bring the maximum yield, the current azimuth (-90°) represents -10.7% loss towards the optimum irradiation on the plane.
- The irradiation sensor is installed at the wrong tilt, and is significantly shaded and soiled.
- Significant near shading effects are caused by the trees surrounding the system.

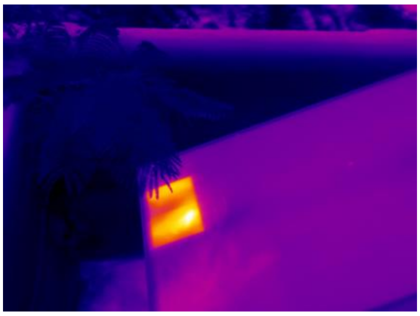

Figure 54: Shading inducing hotspot

- Various module product failures were discovered, such as busbar corrosion, defective J-boxes, hotspot sensitivity and broken glass.

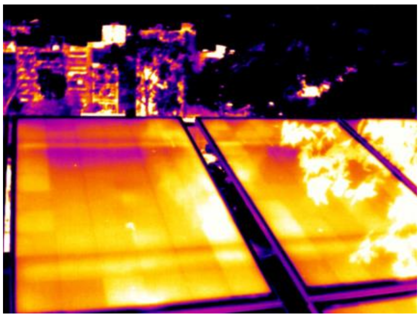

Figure 55: Modules with apparent PID effect

- A combination of installation failures were also present: backsheet scratches, open and loose connectors, mounting structures with sharp edges and corroded elements.

Impact on Performance

- Soiling measurements were conducted measuring both the short circuit current and nominal power before and after cleaning. The estimated soiling loss is on average 2.9%.

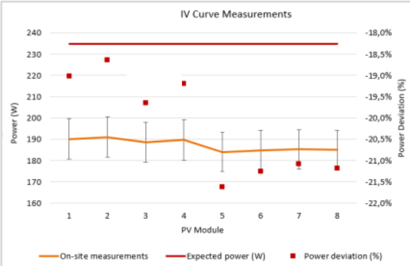

Figure 56: On-site measurements

- PID, at initial stages, could be responsible for 15% of the losses on system level. The degradation is in on intermediate stage.
- Although open J-boxes might not have an impact on the performance, for now, this is an important safety issue that should be addressed. Nearly 40% of the modules were missing the lid.
- The near shadings are responsible for an irradiation reduction on the tilted plane of approx. 4.9% at system level.

Figure 57: Coating thickness - galvanization

- The access to the roof is difficult. This could have caused module damages during transportation, handling and installation, and possibly, performance losses.

Proposed Solutions

- Considering safety and system long-term reliability, the module J-boxes shall be evaluated. Modules with exposed J-boxes (corrosion in the diodes) shall be immediately replaced.
- Manual cleaning cycles shall be increased based on the results of a soiling study.
- An anti-PID box shall be installed to stop module degradation.
- PV modules showing power drops above the warranty conditions shall be replaced. If the replacement is not possible, the modules shall be regrouped according to power and defect classes, within the same string and assigned to individual MPPT (based on infrared inspection with high irradiation levels and after cleaning activities).

Figure 58: Soiling factor measurements

- The irradiation sensor should be properly reinstalled, cleaned and calibrated to ensure accurate readings.

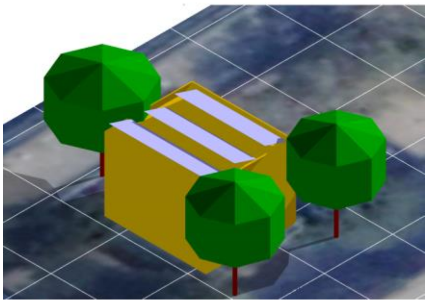

Figure 59: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 16% to 25%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.7 ₹/Wp, 0.7 ₹/Wp/a

Picture Gallery

Figure 60: General view of the system

Figure 61: Module with scratch in the backsheet

Figure 62: Shading and irradiation sensor situation

Figure 63: Loose connectors in the inverter inputs

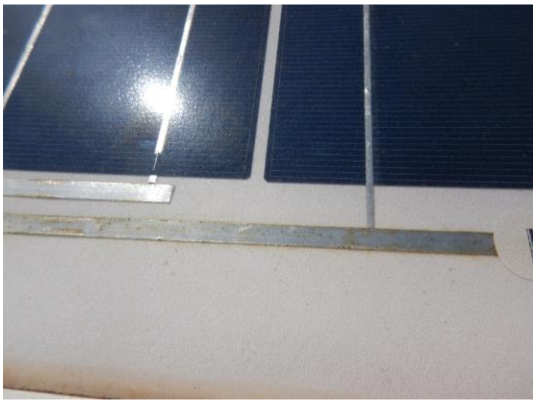

Figure 64: Corrosion in the busbars (lower edge)

Figure 65: Cables in contact with sharp edges

Figure 66: Modules with open J-boxes (ca. 40%)

Figure 67: String with a module with broken glass

5

PV plant: ***IV.5***

Nominal capacity: ***80 kWp***

Average specific yield since COD (March 2014): ***1046 kWh/kWp***

Abstract*: The PV plant is affected by near shadings caused by antennas and lightning rods. Furthermore, the modules show heavy contamination from cement and some poorly produced cells. It is recommended to (i) carry out a deep cleaning of heavily contaminated modules, (ii) replace the roof structures which cause shading on the system, (iii) replace modules exceeding the manufacturer's guaranteed performance drop and (iv) replace modules with defective J-boxes. The estimated production boost caused by the retrofitting actions lies between 10-15%.*

PV Plant's health

Main Findings

- Cable ties broke, hence the module cables and connectors were loosely hanging.
- In some modules, the individual cells fall out of order.

Figure 68: Screws of the fastening clamps

- Several modules have scratches in the front glass.
- The modules present different types of J-box failure types, e.g., overheated, open or missing lid.

Figure 69: Modules with open or missing

- The cables of the irradiation sensor are not installed correctly.
- The cable ducts are brittle and some are broken.
- The combiner box is not attached correctly.

Figure 70: Improper attachment - combiner box

Impact on Performance

- Soiling losses were determined based on the measurements on-site to be 6.9%, on average.
- Several roof structures cause local shading on the system.

Figure 71: Shading through antenna

- Mach modules are contaminated with cement residues that create hot spots.

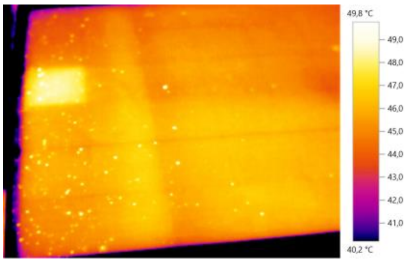

Figure 72: Hot spot due to cement residues

- The Poorly produced cells were found in some modules.

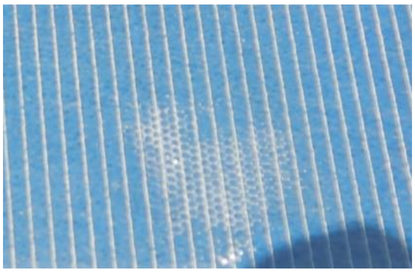

Figure 73: Delamination issues

Proposed Solutions

- Modules with manufacturing defects (i.e., delamination) shall be replaced.
- Modules with any defect on the J-box should be immediate replaced (safety, operation and reliability issues).
- The modules contaminated by cement should be cleaned.
- All of the DC cabling, including the combiner box, should be maintained for proper attachment.
- PV modules showing power drops above the warranty conditions should be replaced. If the replacement is not possible, the modules should be regrouped in power classes within the same string and assigned to individual MPPT.

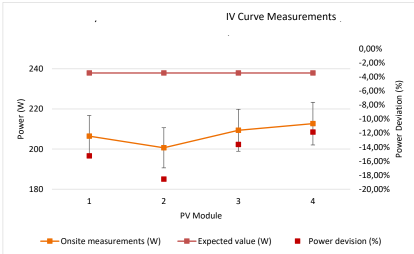

Figure 74: Onsite power measurements

- The roof structures that shade the system should be moved.
- The simulation of the system showed a shading loss of 2.65%.

Figure 75: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 10% to 15%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.1 ₹/Wp, 0.2 ₹/Wp/a

Picture Gallery


Figure 76: DC cables exposed to UV radiation

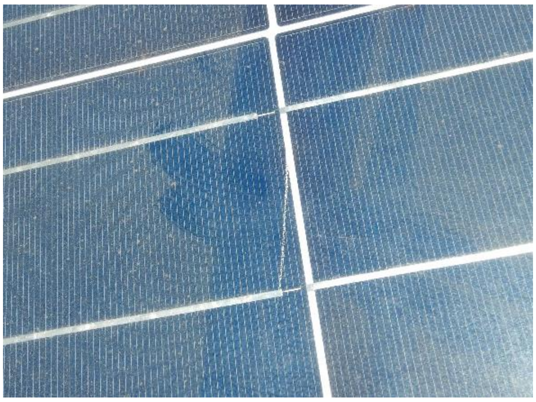
Figure 77: Scratch on front glass

Figure 78: Broken connectors on inverter

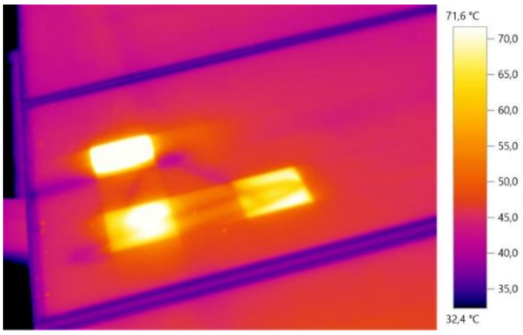

Figure 79: Hot spot caused by shading from antenna


Figure 80: Broken sensor wiring


Figure 81: Broken cable duct


Figure 82: General overview.


Figure 83: Contamination from cement

6

PV plant: ***IV.6***

Nominal capacity: ***40 kWp***

Average specific yield since COD (March 2015): ***1012 kWh/kWp***

Abstract*: The plant is affected by moderate soiling. Due to the difficult access, the O&M activities such as visual inspection and module cleaning, might be disregarded. Several modules were laying on the ground likely due to a combination of a challenging installation and wind loads. It is recommended to (i) replace missing modules and reconnect strings, (ii) improve cleaning cycles, (iii) conduct proper inverter maintenance, (iv) implement anti-PID solutions and (v) re-string with individual MPPT assignments according to mechanical damages (IR inspection). The estimated production boost expected by the retrofitting actions lies between 10-20%.*

PV Plant's health

Main Findings

- The access to the roof is difficult. This could have caused module damages during handling and installation, which would likely lead to underperformance.
- The open wasteland in the proximity of the system could be responsible for increased soiling issues.
- Several modules were laying on the ground (disconnected) likely due to a combination of a challenging installation on the edge and strong wind loads.

Figure 84: String with module with broken glass

- The inverter fan filters (outlets) are partially blocked, leading to a higher risk of inverter shut down.
- PID presence was discovered via on-site IV curve and thermographic inspection.

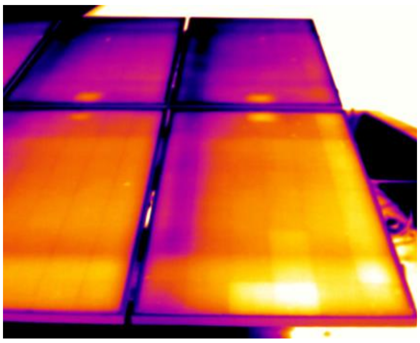

Figure 85: PID affected modules

- Module defects, such as Backsheet label detachment, broken glass and corrosion in the busbars, were also discovered.

Impact on Performance

- Soiling losses of 4.7%, on average, were calculated from IV curve measurements of modules before and after cleaning.
- There is evidence of PID effect, which could result in a performance loss of as high as 15% at the system level, based on PI Berlin on-site measurements (and considering expected power and the soiling factor).
- Based on the simulation, the shading losses are within design values, 1.22%.
- Strings with broken glass could underperform 30% due to irradiation reduction.

Figure 86: Differences in current among strings

Proposed Solutions

- The cleaning cycles shall be increased based on the results of a soiling study that adjusts the cleaning needs to each season (considering the surroundings).

Figure 87: Improvement of cleaning cycles

- Anti-PID measures shall be implemented in order to stop and reverse the degradation. PV modules (without PID), showing power drops above the warranty conditions shall be replaced. If the replacement is not possible, the modules shall be regrouped in power classes within the same string and assigned to individual MPPT.
- Damaged modules by wind loads and broken glass shall be replaced and properly installed.
- Module product defects (corrosion in busbars, defective labels) shall be monitored, whether the degradation continues or it has stabilized.

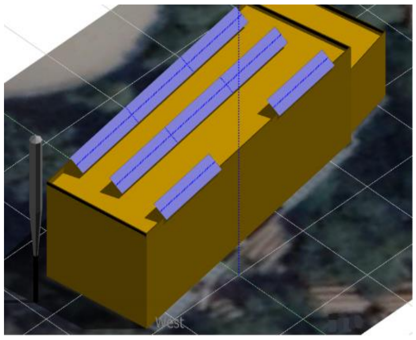

Figure 88: 3D model of the system

Estimated energy boost after conducting the suggested retrofitting actions: 10% to 20%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 2.6 ₹/Wp, 0.3 ₹/Wp/a

Picture Gallery

Figure 89: General view of the system

Figure 90: Rooftop access (limited access to O&M)

Figure 91: Strings in open circuit (broken modules)

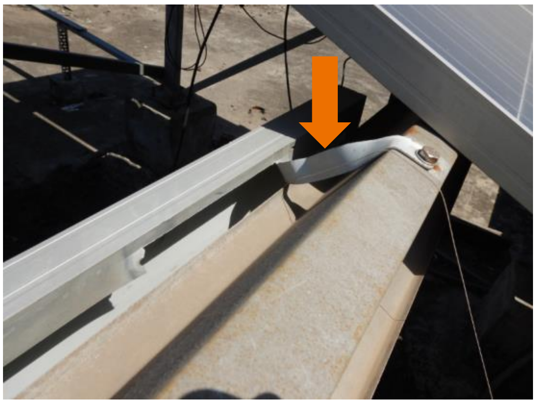

Figure 92: Broken modules likely due to strong winds

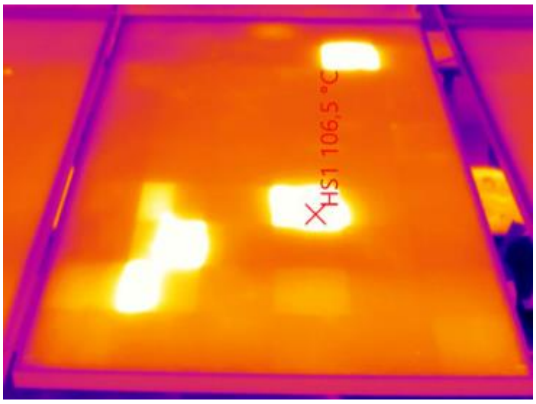

Figure 93: String with module with broken glass

Figure 94: Inverter fan filters (outlet) partially blocked

Figure 95: Hot connector at the inverter

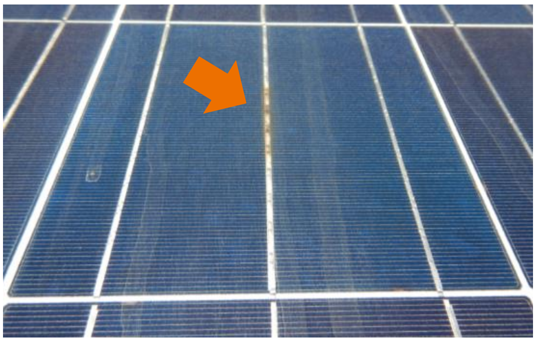

Figure 96: Modules with busbar corrosion

7

PV plant: ***IV.7***

Nominal capacity: ***20 kWp***

Average specific yield since COD (March 2015): ***1041 kWh/kWp***

Abstract*: The PV plant is affected by nearby shading from trees and roof structures. The electroluminescence investigation showed some micro cracks and isolated parts. Furthermore, the DC wiring is not installed correctly. It is recommended to (i) replace the broken modules, (ii) increase the cleaning frequency, (iii) replace modules exceeding the manufacturer's guaranteed performance drop and (iv) fix shading problems. The estimated production boost caused by the retrofitting actions lies between 12-18%.*

PV Plant's health

Main Findings

- The system grounding is not installed securely.
- String cables damaged by or in contact with sharp edges were spotted.

Figure 97: Cables in contact with sharp edge

- The cables of the irradiation sensor are not installed correctly.
- The connectors of the string cables at the inverter are not correctly attached.
- Some cables are insulated with duct tape.

Figure 98: Broken cable ducts

- Cable ties broke, hence the module cables and connectors are loosely hanging.
- The bending radius of the string cables is respected only partially.
- Some parts of the cables are exposed to UV radiation. And some cable ducts have already broken.
- Some of the labels detach from the modules.

Impact on Performance

- In some places, the string cables are combined in cable bundles that heat up.

Figure 99: Overheated plugs

- Several hot spots were discovered in the plant.

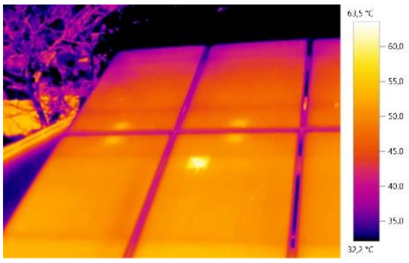

Figure 100: Soiling induced hotspots

- Based on the amount of cracks and broken cells and corresponding inactive areas, the power loss is estimated to be 5% at the system level.

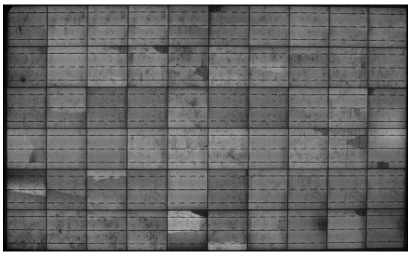

Figure 101: Microcracks and isolated parts

- Near shading is caused from nearby trees on the South side of the plant and installed antennas on the roof.
- There are modules with broken front glass.

Proposed Solutions

- All DC wiring should be maintained.
- The cleaning frequency should be increased and the strong local contamination should be removed.
- PV modules showing power drops above the warranty conditions should be replaced.

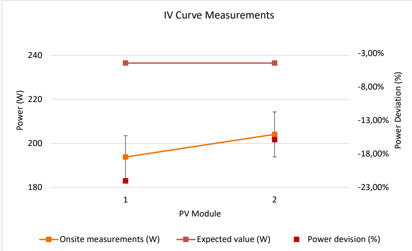

Figure 102: Onsite power measurements

- The shading caused by trees or roof structures should be mitigates.
- Broken modules shall be immediately replaced.
- Module product defects (detached labels) shall be monitored, whether the degradation continues (potential claim) or it has stabilized.
- The grounding of the entire system should be checked.
- The simulation of the system showed a shading loss of 5.9%.

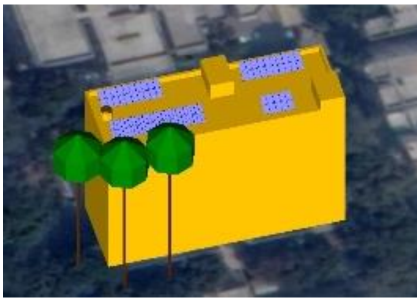

Figure 103: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 12% to 18%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 2.5 ₹/Wp, 0.3 ₹/Wp/a

Picture Gallery


Figure 104: Critical bending radius


Figure 105: Open and broken cable ducts


Figure 106: Module label issues

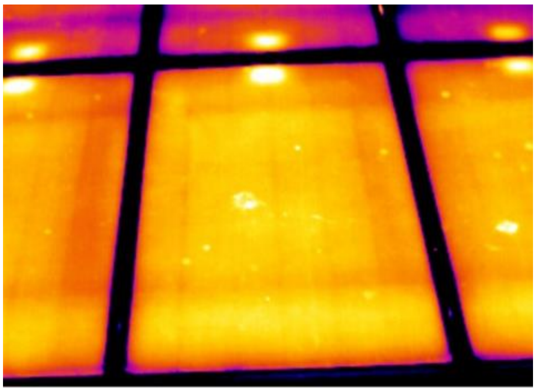
Figure 107: Hot spots induced by bird drops


Figure 108: Loose hanging cables


Figure 109: Corrosion in bus bars


Figure 110: General overview


Figure 111: Shading from antenna

8

PV plant: ***IV.8***

Nominal capacity: ***80 kWp***

Average specific yield since COD (March 2015): ***1048 kWh/kWp***

Abstract*: The system's DC cabling is in poor condition and should be fixed. The monitoring system shows incorrect values and the system is partially shaded by trees and cables. Furthermore, the modules showed substantial underperformance and some are affected by shunts. It is recommended to (i) repair the monitoring system, (ii) improve plant cleaning, (iii) replace modules exceeding the manufacturer's guaranteed performance drop and (iv) replace modules with defects shunts or broken diodes. The estimated production boost caused by the retrofitting actions lies between 5-14%.*

PV Plant's health

Main Findings

- String cables damaged by or in contact with sharp edges were spotted.
- The monitoring of the system shows PR values of 100%. This indicates incorrect input values from the sensors.

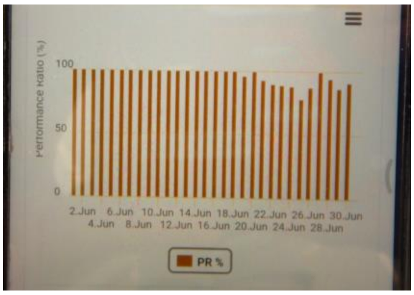

Figure 112: Mobile plant monitoring

- The radiation sensor cables are not installed correctly.
- Some parts of the cables are exposed to UV radiation. Pipes conveying cables are open and some parts have already broken.

Figure 113: Broken cable ducts

- The grounding of the system is interrupted in some places and is therefore not guaranteed.
- The inlets and outlets of the ventilation system of the inverters are dirty.
- Cable ties broke, hence the module cables and connectors are loosely hanging.
- Some modules have oxidized bus bars.

Impact on Performance

- Based on the measurements on-site, soiling losses were determined to be 5.2%, on average.
- Several modules with shunt damage were found during the visual inspection.

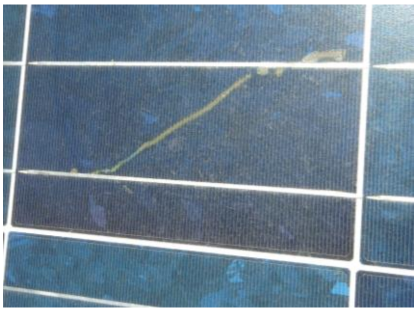

Figure 114: Snail trail pattern on module

- Some modules have local contamination that leads to hotspots.

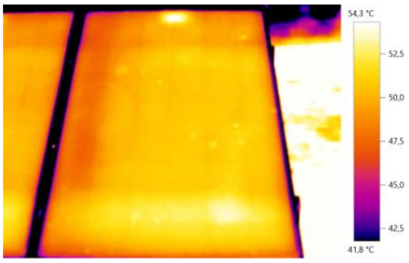

Figure 115: Near shading by trees

- Some parts of the plant are permanently shaded by trees or cables.

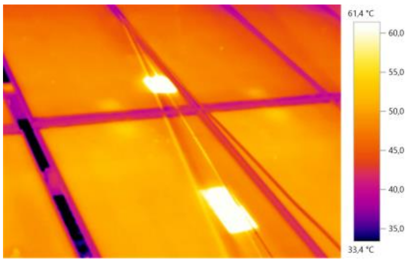

Figure 116: Shading induced hotspots

- A module with an active diode was found.

Proposed Solutions

- The entire DC wiring should be checked for safety.
- Broken modules that do not meet the warranty requirements should be replaced.
- Local shading caused by trees or cables should be removed.
- The frequency of cleaning should be increased and significant dirt should be removed.
- PV modules showing power drops above the warranty conditions should be replaced. If the replacement is not possible, the modules should be regrouped in power classes within the same string and assigned to individual MPPTs.

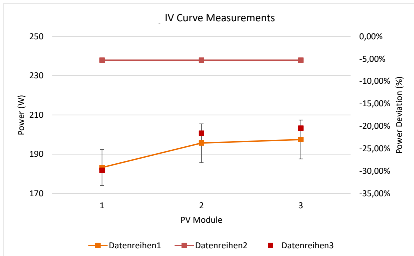

Figure 117: Onsite power measurements

- The radiation sensors should be calibrated.
- The simulation of the system showed a shading loss of 1.5%.

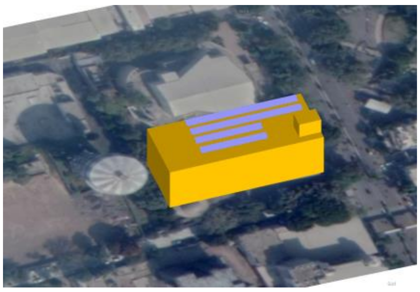

Figure 118: 3D model constructed in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 5% to 14%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.8 ₹/Wp, 0.2 ₹/Wp/a

Picture Gallery

Figure 119: Non-functional grounding

Figure 120: Broken ground wire

Figure 121: Loose/hanging cables

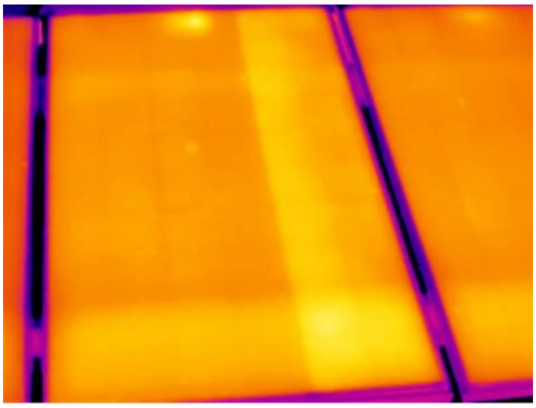

Figure 122: Active diode

Figure 123: Poorly installed sensor cables

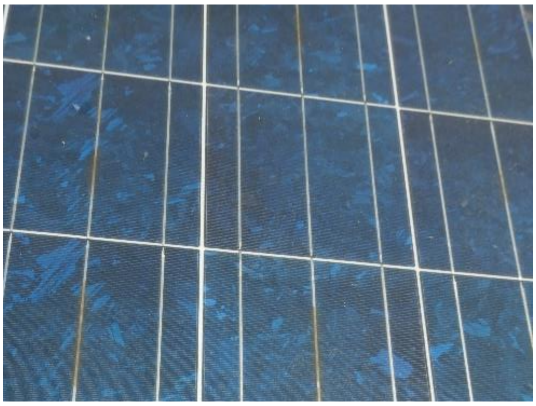

Figure 124: Broken and burned cells

Figure 125: General overview.

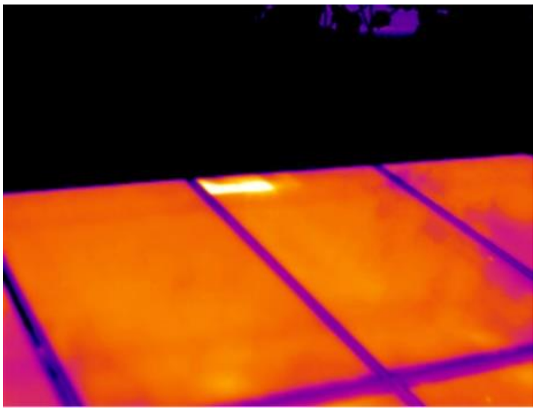

Figure 126: Shading situation: trees

9

PV plant: ***IV.9***

Nominal capacity: ***100 kWp***

Average specific yield since COD (March 2015): ***1065 kWh/kWp***

Abstract*: The plant is affected by significant city pollution, minor near shadings and bird drops. Additionally, isolation and safety issues cannot be excluded due to damaged cables by sharp edges. Electroluminescence imaging exposed different module mechanical damages, likely induced during handling and installation. It is recommended to (i) conduct a string reengineering with individual MPPT assignment, based on IR inspection, (ii) improve O&M activities (particularly cleaning) and, (iii) retrofitting of DC cable (sharp edges, bending radius). The estimated production boost expected by the retrofitting actions lies between 8-14%.*

PV Plant's health

Main Findings

- The system displays poor cable management, e.g., loose connectors, cables in contact with sharp edges and loose DC cables behind the modules.
- Through IR inspection, hotspots induced by soiling, near shading and cracks were detected.

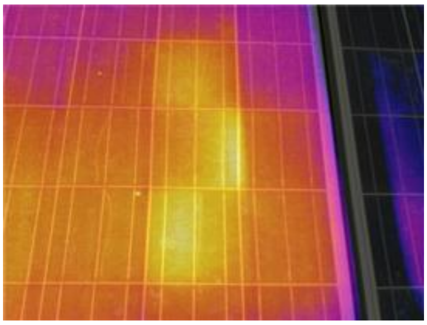

Figure 127: High temperature cracks (IR)

- Electroluminescence imaging revealed an important variety of cell cracks.

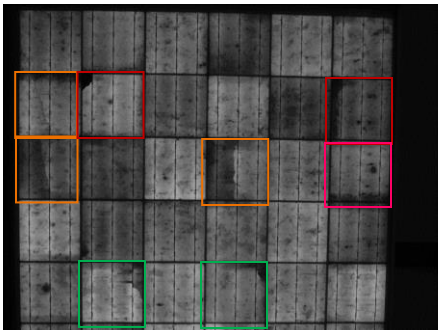

Figure 128: Module with multiple cracks

- Module defects, such as snail trails, label detachment, corrosion in the busbars, and modules with tight bending radius were discovered.
- The inverter fan filters (outlets) are partially blocked, leading to a higher risk of inverter shut down.
- The calibration date of the irradiation sensor was not provided.

Impact on Performance

- Soiling measurements were conducted measuring nominal power before and after cleaning at irradiations higher than 900 W/m². The estimated soiling factor is in the range of 5-6%.

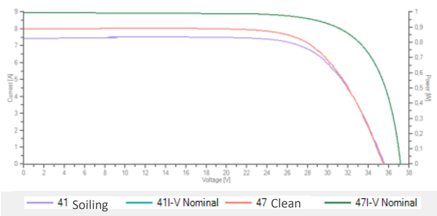

Figure 129: on-site soiling measurements

- The losses due to near shadings could represent 2.3% less irradiance loss, based on a representative simulation.
- Due to the limited access to the rooftop (staircases) it is likely that the modules suffered increased mechanical loads during transportation, handling and installation. The amount and type of cracks discovered via EL, as well as the snail trail distribution, could be an indicator of a performance drop between 5-10%.

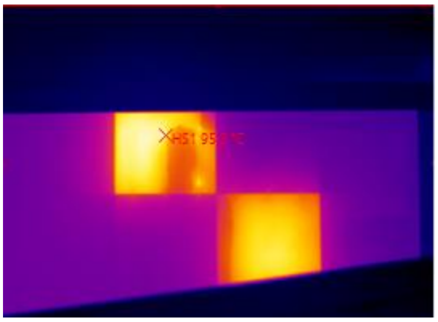

Figure 130: Module with hotspots

Proposed Solutions

- Modules with a large amount of cracks (including snail trails), shall be regrouped in the same string or at least assigned to one MPPT. The grouping shall be conducted based on infrared inspection with high irradiation levels and after cleaning activities.
- The manual cleaning cycles shall be implemented and scheduled based on the results of a soiling study that adjusts the cleaning needs to each season.

Figure 131: Improvement of cleaning cycles

- The lack of calibration of the irradiation sensor will not directly affect the performance of the system. However, the accurate recording of the onsite irradiation will provide confidence to the plant`s KPIs.
- Damaged cables (sharp edges) shall be replaced. Furthermore, the minimum bending radius shall always be respected.
- Snail trails shall be monitored to validate whether they have stabilized over time.

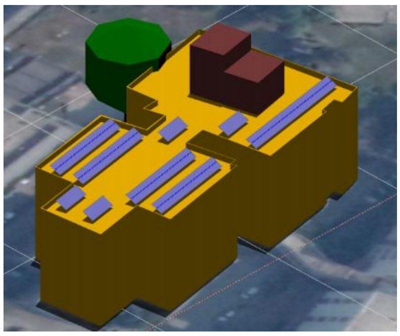

Figure 132: 3D scene in in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 8% to 14%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 1.3 ₹/Wp, 0.2 ₹/Wp/a

Picture Gallery

Figure 133: General view of the system

Figure 134: Fixed tilt mounting structure foundations

Figure 135: Modules with busbar corrosion

Figure 136: DC cabling management

Figure 137: Advanced degradation cracks & hotspots

Figure 138: Lightning arrester without spikes

Figure 139: Cables damaged by sharp edges

Figure 140: Irradiation sensor – plane of array

10

PV plant: ***IV.10***

Nominal capacity: ***100 kWp***

Average specific yield since COD (April 2013): ***1074 kWh/kWp***

Abstract*: The plant is strongly affected by snail trials. The origin is likely a combination of mechanical loads, from handling and installation (microcracks) and poor backsheet quality. However, the impact on the performance cannot be completely addressed without proper thermographic inspection and on-site power measurements. It is recommended to (i) analyze the evolution of snail trails and hotspots via yearly thermographic inspection of the modules, (ii) improve cleaning cycles based on soiling study and (iii) replace modules exceeding the manufacturer's guaranteed performance drop and product warranties. The estimated production boost expected by the retrofitting actions lies between 5-15%.*

PV Plant's health

Main Findings

- Although installed next to a large field, moderate soiling was detected.
- The inverter was found in a stand-by mode, i.e., disconnected from the grid.
- The majority of the modules presented a snail trail pattern, from moderate to severe stages.

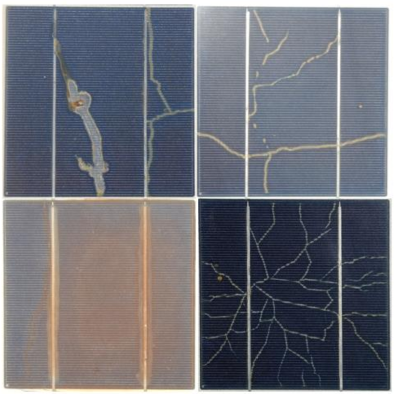

Figure 141: Examples of "cracks" found

- Due to the difficult access to the roof, it is likely that the modules suffered mechanical stress during transport, handling and installation. The resulting microcracks are one of the sources of the snail trail effect in the modules.

Figure 142: Damaged cables: sharp edges

- String cables were occasionally spotted in contact with sharp edges, showing initial signs of damage.
- The plant was installed in a single module landscape orientation, with a very limited interrow spacing.

Impact on Performance

- Based on the simulation, shading losses are estimated to be 5% at the system level.
- Due to the inverter status during the IR inspection (disconnection, open-circuit), the thermographic analysis could not take place to evaluate PID. Based on on-site IV curve measurements, the PID effect could be responsible for 10-15% energy losses.

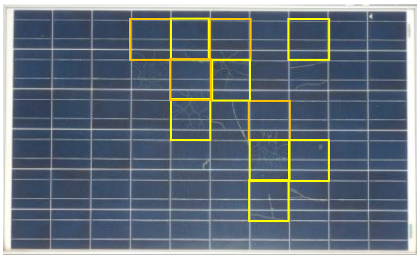

Figure 143: Cell degradation (snail trials)

- The module sample tested on-site showed a significant drop in the expected performance.

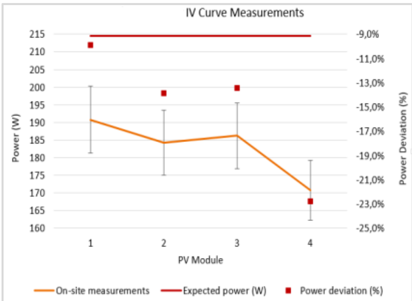

Figure 144: On-site IV curve samples

- An average soiling factor of 3% was determined from IV curve measurements of sample modules, before and after cleaning.
- The lack of calibration of the irradiation sensor will not directly affect the performance of the system. However, the accurate recording of the onsite irradiation will provide c plant`s KPIs.

Proposed Solutions

- The snail trails shall be monitored and assessed (via IR) whether the degradation has reached stabilization.
- Modules with snail trails within similar degradation shall be re-grouped in the same strings, or at least assigned to one MPPT. The grouping shall be conducted based on infrared inspection with high irradiation levels and after cleaning activities.
- PV modules showing power drops caused by product defects above the warranty conditions shall be replaced (7 yrs in operation < 10yrs - 90% power performance).
- Cleaning cycles shall be increased and defined based on a soiling study that adjusts the cleaning needs to each season. Cleaning once a month during the dry season is not enough.
- Damaged cables shall be replaced and those in contact with sharp edges shall be protected.
- The inverter configuration (i.e., "waiting for sun") shall be validated to eliminate the possibility of an internal failure. This issue shall be only related to "DC voltage not sufficient to allow for connection to the main network".

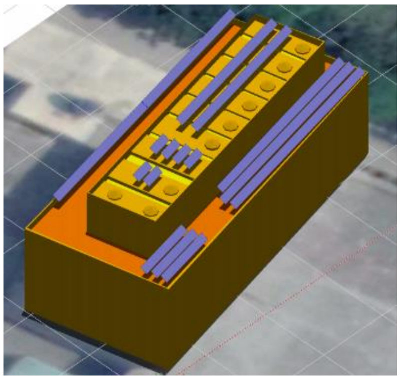

Figure 145: 3D model in PVsyst

Estimated energy boost after conducting the suggested retrofitting actions: 5% to 15%
Estimated costs of proposed retrofitting actions (CAPEX, OPEX): 0.8 ₹/Wp, 0.2 ₹/Wp/a

Picture Gallery

Figure 146: General view (north rooftop)

Figure 147: Drainage partially blocked

Figure 148: Rooftop access (north building)

Figure 149: Equipotential bonding (cable management)

Figure 150: Advanced cell degradation (temperature)

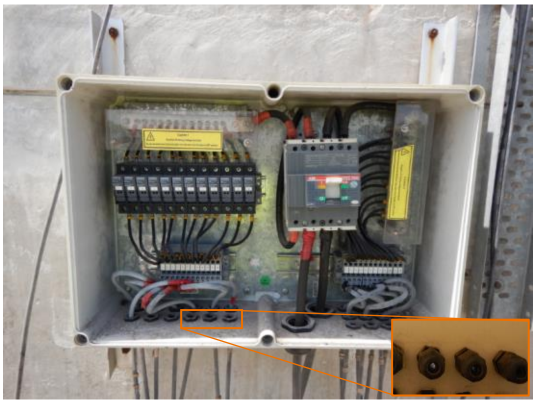

Figure 151: Combiner box with open glands

Figure 152: Inverter status (waiting sun/grid)

Figure 153: IV Curve & Soiling measurements

8. Lessons Learned and Outlook for the Next Generation Projects

The results of the evaluation of each of the 10 PV plants exposed in the previous section, will be used in this chapter to shed some light on three fundamental questions.

8. 1. Which findings arise more often and which have the highest impact on the performance?

The following chart shows the top findings detected on-site having a negative impact on the performance of the analyzed PV plants. The number at each bar shows in how many PV plants each finding was present.

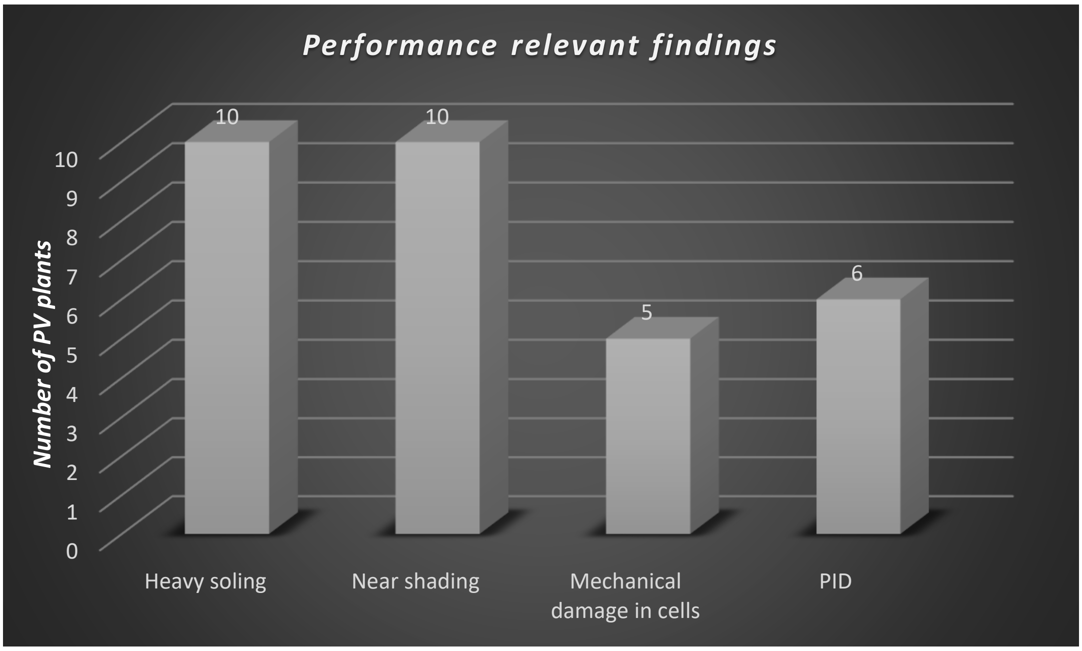

Figure 154: Chart showing in how many PV plants each finding is present (sample: 10 plants)

It can be seen how *heavy soiling* and *near shading* appear in nearly every PV plant. *Potential Induced Degradation (PID)* is a finding associated to unexpected module degradation mechanism caused by a combination of (i) negative potential, (ii) high temperatures and (iii) high humidity rates. PID is a defect that can be prevented taking the appropriate measures during the design phase. Then, *mechanical damages in cells,* which is related to the electromechanical integrity of the modules, is a defect that also appears in a large number of sites and it is highly likely caused by improper module handling, during the installation and operation phase[4].

As described in chapter 7, the access for many of the sites might have compromised the integrity of the cells within the PV modules. Although some product failures might not be performance-relevant now, i.e., open J-boxes, they will likely become relevant when, for example, the diodes breakdown due to environmental exposure, ultimately leading to open-circuit strings. For some systems, this represents nearly 40% of the modules.

[4] *Walking and stepping on the modules also contributes to the appearance of cell damages*

Snail trails was another common issue in the last plants inspected. The degradation is already in a rather advanced stage that in combination with soiling and shading issues could lead to hotspots. It should be periodically monitored and evaluated via infrared inspection whether the snail trails have reached stabilization.

The low performance of the inspected PV plants is caused by a mix of (i) heavy soiling, (ii) near shading and (iii) high module degradation rates.

Another aspect that also contributes to the loss of energy production is an operation and maintenance plan below market standards. Specifically, the lack of spare parts on site coupled with relaxed reaction times, are two aspects that directly result in loss of performance and availability, and therefore, underperformance. None of the PV plants had properly installed weather stations, spare parts on-site, and moreover, no written agreement setting the contractual reaction times.

The absence of O&M contracts stating clear procedures for the corrective maintenance plan, the reaction times, the Performance Ratio monitoring and the contractual availability values, is a key factor that contributes decisively to lowering the PV plant's output.

In regard to underperforming systems, modules with power performance considerably under the expected values[5] were discovered in a significant number of PV plants. This issue shall be further addressed in cooperation with the developer, installer (EPC) and/or module manufacturer, and, when applicable (according to the specific installation contracts and the guarantees included), initiate the adequate claim. The following graph shows highest impacts on the performance from the aforementioned findings of the inspected PV plants. The graph also indicates the maximum energy loss values associated to each of these findings[6].

[5] *The power is corrected taking into account the light induced degradation and yearly natural degradation, according to the amount of years in operation, flash-lists (when available) and label values.*

[6] *These values have been calculated by PI Berlin through (i) estimates based on PI Berlin's long-term experience, (ii) 3D simulation, (ii) processing of data obtained directly on site by means of special equipment.*

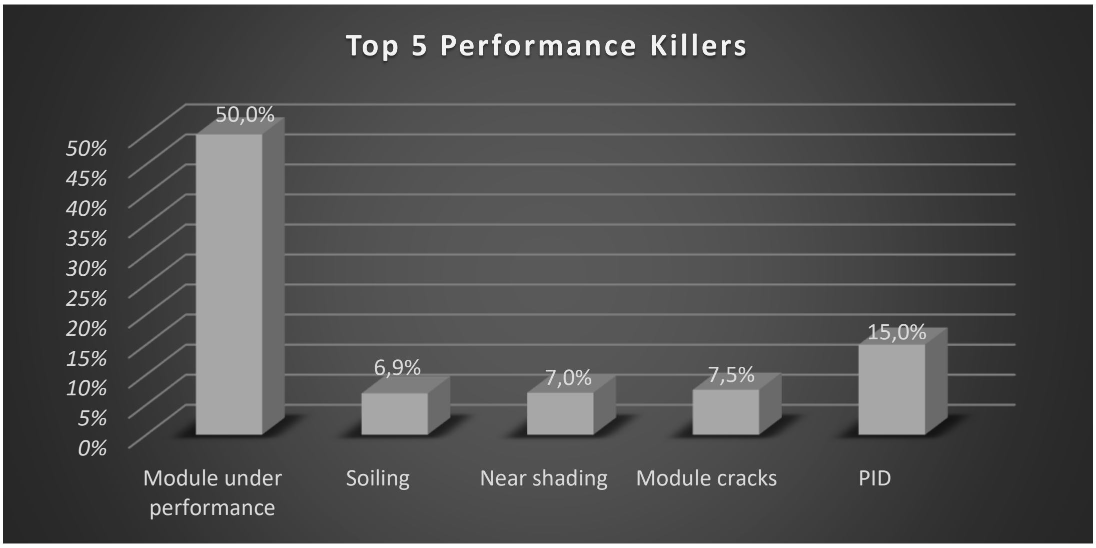

Figure 155: Top 4 findings with the highest performance impact on the inspected PV plants

As shown in the graph, underperforming modules (due to higher degradation rates and potentially advanced stage of Potential Induced Degradation) could lead to a yield loss of 15% at system level. In some of the examined plants, this high degradation value has been reached within months. This rapid degradation could be explained by a high PID sensitivity of the PV cells in the installed modules, in combination to the typical hot and humidity conditions. The presence of bird droppings, debris or pollution, result in soiling losses close to 7% for some of the systems. In this regard, it is important to understand that some PV plants visited by PI Berlin underwent cleaning activities a few days before the inspection. Hence, the values measured on-site by PI Berlin can therefore be greatly exceeded if cleaning activities are disregarded, particularly during the dry season.

According to PI Berlin's calculations, the global losses at the system level caused by *PID* exceed 15% within months, while the losses associated with soiling can widely exceed 10% in the dry season.

The losses caused by near shading are estimated to be around 7% in some of the inspected PV plants. Although it may give the impression that these losses are difficult to avoid since they are a consequence of near buildings, rooftop objects and vegetation, a proper site assessment prior installation would have probably reduced this issues. Moreover, this subject shall be properly addressed during the design phase, since after the installation, only mitigation actions can be implemented. Furthermore, shading losses caused by trees can only be reduced in case the trimming is allowed by the authorities. Finally, the losses associated with mechanical damage of cells can reduce the production of some PV plants in 7-9% according to PI Berlin's estimations.

In some of the inspected PV plants, the losses caused by near shading exceed 7% according to PI Berlin's estimations. In PV plants with severe mechanical damage at the module level, the nominal power of the PV plant can be reduced by up to 8%.

Worldwide, PV manufacturers have developed advanced production and inspection techniques to ensure that the "dispatched modules" have a limited amount of product failures, such as microcracks. Moreover, PI Berlin' long-term experience in the matter indicate that most of the *mechanical stress induced cracks* occur during handling and module installation, as well as during O&M activities. However, the assessment of cracks in operating PV modules is not an easy task since the crack distribution will not certainly lead to a homogenous power degradation. Additionally, since the warranties[7] offered by the installation company are limited to the product and do not include workmanship, the module damages from mishandling during the installation remain contractually uncovered.

8. 2. Which retrofitting solutions can be implemented to boost the energy production of the inspected PV plants?

It would be fair to mention that Pune sites, in general, were slightly better than the previous locations within this project. Nevertheless, these PV plants also exposed some of the most common failure modes, not only in the Indian market, but worldwide. PI Berlin suggests 5 retrofitting actions to partially mitigate the negative consequences of the findings described in the previous section. The most important actions associated to these retrofitting actions are described below:

Improvement of module cleaning frequency. The source of soiling in most of the inspected PV plants is either bird droppings, city pollution, debris or a combination of all three. In order to figure out what the optimum cleaning interval is, the output of clean[8] and dirty strings shall be compared for at least 3 months. As soon as the difference in the output leads to a loss of revenue that offsets the cleaning costs of the whole plant, a cleaning visit will be needed. This study will be performed separately for the dry and rainy season, as natural cleaning comes into place in the rainy months. Cleaning becomes particularly relevant in those plants where the modules are mounted with very flat angles.

[7] *In some cases, the EPC warranty has also expired without a Final Acceptance Test or proper commissioning.*
[8] *The clean strings are used as a benchmark and will be cleaned every day.*

Re-sorting of modules and strings. A re-sorting of the modules shall be conducted in those cases where the present configuration leads to significant mismatch at inverter level or to low output currents of some strings due to the low performance of individual modules. Modules affected by heavy cracks with isolated cell sections that induce hotspots, shall be grouped in the same strings. In those cases where the output voltage of low performing strings affects significantly the string voltage, “good” and “bad” strings shall be assigned to different MPP trackers. The distinction between good and bad strings and between damaged and not damaged modules can be conducted with a multimeter and an infrared camera respectively. The infrared inspection shall be conducted after cleaning and at irradiation values higher than 800W/m².

Module replacement. The replacement of the modules should only be carried out if the cost of the components is borne by the manufacturer. This case will only occur (i) if the manufacturer still exists, (ii) if the reasons why the replacement is required are due to product defects or a loss of performance higher than the guaranteed values, and (iii) if the warranties are still active. The manufacturer's warranties do not cover damages caused by bad handling or improper installation and poor O&M practices.

Shorten module strings. In situations where the near shadings seriously affect the energy generation of the modules, it is recommended to shorten the strings by reducing the number of modules connected in series. The strings will be grouped by MPPTs at the inverter level to reduce as much as possible the voltage mismatch. DC/DC converters may be necessary at the inverter input in cases where the minimum MPP voltage is not reached under operating conditions.

Increase of the albedo factor. A possible alternative to extra-boosting the yield is to paint the surface with light colors, cover the ground with white gravel and/or stick reflective materials to the walls and shading objects surrounding the PV modules. These measures aim at increasing the overall albedo factor to 0.5 and thus, the amount of kWh/m² reaching the PV module plane of array. Glaring of neighboring buildings shall be avoided.

Depending on the status of each PV plant, and as long as the future O&M contractor has sufficient personnel and budget, all or only some of the abovementioned measures can be applied. In any case, the measures proposed by PI Berlin do not imply huge investments and can be implemented with a reasonable budget. The measures suggested by PI Berlin must be complemented with a reinforcement of the commercial conditions in the O&M contracts, mainly in regards to (i) the reduction of the reaction times and (ii) the storage of spare parts needed to commit to the said reaction times.

PI Berlin suggests 5 retrofitting actions that depending on the status of each PV plant may lead to a performance boost between 5% and 20%. Furthermore, these actions do not require large investments in the OPEX.

Besides the retrofitting actions suggested to increase the energy generation, any necessary improvements to operate the PV plants in a safe environment shall also be carried out.

These safety improvements shall be conducted regardless how high or small the estimated performance boost is[9].

8. 3. Which mechanisms are needed to avoid underperformance and to ensure the revenues in the next generation projects?

Problems caused by wrong decisions taken during the design phase can only be partially solved during the operational phase. Therefore, preventive measures shall be applied in order to save costs and time at later stages. PI Berlin makes the following suggestions based on the issues and findings detected during the assessment of the 10 PV plants:

1. An energy yield assessment shall be conducted during the development phase. That said, it shall consider all shading objects that might have an impact on the system performance. This will help to avoid overestimations of the yearly output and an inaccurate modelling of the cash flows.
2. Where near shadings seem to pose a significant impact in the energy production, module strings shall be sized with less modules and they shall be grouped accordingly. Near shading losses higher than 5% shall be avoided.
3. Self-shading between rows shall be kept as low as possible. Lower tilt angles help achieving this goal.
4. The PV plants shall not deviate more than 30° from true South. Aligning the PV plant´s layout to the orientation of the building is not always the optimal solution.
5. All PV plants shall be *commissioned* before handover, according to the industrial best practices. These practices shall include, besides all safety tests specified in the IEC 62446, a PR test of at least 5 days and an infrared inspection of 100% of the PV modules, inverters and cables. The reliability of the SCADA system and the weather station shall be evaluated as well.
6. In case of lack of experience, the installation and O&M teams shall be trained to avoid damages on the PV modules, during daily activities.
7. The O&M contracts shall include clear indications on the expected reaction times, intervention plan during corrective maintenance, preventive maintenance plan, spare part management, reporting, contractual availability values and SCADA visualization. These topics shall be tailor made to the needs of each individual PV plant.[10]

[9] *An example of this is the installation of a safety lifeline (when applicable) or the replacement of damaged cables and modules (from broken Jbox or glass).*

[10] *This recommendation may be difficult to implement for small rooftop systems*

8. The module cleaning frequency shall be adjusted after the first year based on the methodology described in chapter 8.2.
9. The EPC contract shall include dedicated sections describing the best practices for installation and commissioning activities, as well as the *pass and fail* criteria for handover, with its associated penalties.[11]
10. Each PV plant shall include a weather station with at least (i) one irradiation sensor on the tilted plane (GTI), (ii) one ambient temperature sensor and (iii) one module temperature sensor. All sensors shall be properly installed according to the manufacturer's requirements. The irradiation sensor shall be calibrated, at least, every 2 years. It shall be kept clean and at the right tilt, in order to ensure an accurate and representative PR calculation.

[11] *This recommendation may be difficult to implement for small rooftop systems*

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Annex I – IV Curve Tracing Results

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Impp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
1	1	174	193,6	34,2	27,2	7,1	7,8	1061	57	73	Dirty	-	-	-	17,5%
1	1	175	192,7	34,2	26,5	7,3	7,8	1077	57	72	Dirty	-	-	-	17,9%
1	1	176	192,1	34,0	26,3	7,3	7,9	1091	59	72	Dirty	-	-	-	18,2%
1	2	177	101,2	28,6	18,7	5,4	7,3	949	57	48	Dirty	-	-	-	56,9%
1	2	178	101,2	28,6	18,7	5,4	7,3	942	57	48	Dirty	-	-	-	56,9%
1	2	179	101,2	28,5	18,7	5,4	7,3	938	56	48	Dirty	7,1	888	-	56,9%
1	3	180	194,2	34,0	26,5	7,3	7,9	920	56	72	Dirty	-	-	-	17,3%
1	3	181	194,8	34,0	26,6	7,3	7,9	917	56	72	Dirty	-	-	-	17,0%
1	3	182	194,5	34,0	27,0	7,2	7,9	916	56	72	Dirty	7,5	901	-	17,1%
1	4	183	195,3	34,1	27,1	7,2	7,9	903	56	73	Dirty	-	-	-	16,8%
1	4	184	196,4	34,1	26,7	7,4	7,9	907	56	73	Dirty	-	-	-	16,3%
1	4	185	195,5	34,0	26,7	7,3	7,9	912	57	73	Dirty	7,6	901	-	16,7%
1	4	186	210,5	34,7	27,3	7,7	8,2	836	50	74	Clean	-	-	-	10,3%
1	4	187	209,6	34,7	27,7	7,6	8,2	834	50	73	Clean	-	-	-	10,7%
1	4	188	209,4	34,7	27,2	7,7	8,2	826	50	74	Clean	-	-	-	10,8%
1	3	189	209,2	34,4	27,1	7,7	8,4	815	51	73	Clean	-	-	-	10,9%
1	3	190	209,9	34,4	27,2	7,7	8,4	810	51	73	Clean	-	-	-	10,6%
1	3	191	209,4	34,4	27,1	7,7	8,4	808	51	73	Clean	-	-	-	10,8%
1	2	192	103,5	28,3	18,0	5,8	7,7	798	51	48	Clean	-	-	-	55,9%
1	2	193	104,2	28,2	18,5	5,6	7,7	795	51	48	Clean	-	-	-	55,6%
1	2	194	103,6	28,2	18,0	5,8	7,7	797	51	48	Clean	-	-	-	55,9%
1	1	195	205,2	34,4	27,5	7,5	8,3	777	52	72	Clean	-	-	-	12,6%
1	1	196	205,9	34,4	27,1	7,6	8,3	774	52	72	Clean	-	-	-	12,3%
1	1	197	205,7	34,3	27,1	7,6	8,3	777	52	72	Clean	-	-	-	12,4%
2	1	86	211,1	36,7	29,3	7,2	7,9	964	53,5	73,0	Dirty	-	-	-	-44,3%
2	1	87	211,5	36,7	29,2	7,2	7,9	964	53,5	73,0	Dirty	-	-	-	-44,0%
2	1	88	210,7	36,7	29,2	7,2	7,9	964	53,5	73,0	Dirty	-	-	-	-44,5%
2	2	89	207,6	36,3	28,8	7,2	7,8	910	56,0	74,0	Dirty	-	-	-	-46,6%
2	2	90	207,9	36,4	28,8	7,2	7,8	910	56,0	74,0	Dirty	-	-	-	-46,4%
2	2	91	207,1	36,4	28,8	7,2	7,7	910	56,0	74,0	Dirty	-	-	-	-47,0%
2	3	92	207,9	37,0	29,5	7,1	7,6	942	55,1	74,0	Dirty	-	-	-	-46,5%
2	3	93	208,6	37,0	29,4	7,1	7,7	942	55,1	74,0	Dirty	-	-	-	-46,0%
2	3	94	209,6	36,9	29,4	7,1	7,7	942	55,1	73,0	Dirty	-	-	-	-45,3%
2	4	96	199,7	36,7	29,3	6,8	7,4	990	55,3	74,0	Clean	-	-	-	-52,5%
2	4	97	185,5	36,6	29,0	6,4	6,9	990	55,3	74,0	Clean	-	-	-	-64,1%
2	4	98	184,4	36,6	29,1	6,3	6,8	990	55,3	74,0	Clean	-	-	-	-65,1%
2	1	99	210,4	36,1	28,7	7,3	8,0	848	51,0	73,0	Clean	-	-	-	-44,8%
2	1	100	211,8	36,1	28,7	7,4	8,1	848	51,0	73,0	Clean	-	-	-	-43,8%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Impp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
2	1	101	210,2	36,0	28,6	7,4	8,1	848	51,0	72,0	Clean	-	-	-	-44,9%
2	3	102	214,5	37,4	29,5	7,3	7,7	796	52,0	74,0	Clean	-	-	-	-42,0%
2	3	103	215,7	37,4	29,7	7,3	7,7	796	52,0	75,0	Clean	-	-	-	-41,2%
2	3	104	213,7	37,4	30,0	7,1	7,7	796	52,0	74,0	Clean	-	-	-	-42,5%
2	3	105	211,6	37,3	29,9	7,1	7,7	796	52,0	74,0	Clean	-	-	-	-43,9%
3	1	106	221,3	36,6	29,3	7,6	8,4	1049	56,0	72,0	Dirty	9,4	1052	5822	-7,5%
3	1	107	218,8	36,5	29,0	7,5	8,3	1049	56,0	72,0	Dirty	9,4	1052	5822	-8,7%
3	1	108	220,1	36,6	28,8	7,7	8,4	1049	56,0	72,0	Dirty	9,4	1052	5822	-8,1%
3	2	109	221,7	36,2	29,5	7,5	8,1	1055	57,0	76,0	Dirty	7,3	1035	-	-7,3%
3	2	110	220,0	36,2	29,3	7,5	8,0	1055	57,0	76,0	Dirty	7,3	1035	-	-8,1%
3	2	111	221,6	36,1	29,4	7,5	8,1	1055	57,0	75,0	Dirty	7,3	1035	-	-7,4%
3	3	112	209,4	36,4	28,6	7,3	7,9	1047	57,0	73,0	Dirty	5,4	1063	5823	-13,6%
3	3	113	211,9	36,5	28,8	7,4	8,0	1047	57,0	73,0	Dirty	5,4	1063	5823	-12,3%
3	3	114	212,5	36,5	28,4	7,5	8,0	1047	57,0	73,0	Dirty	5,4	1063	5823	-11,9%
3	4	115	221,5	36,8	29,6	7,5	8,1	1066	54,0	74,0	Dirty	9,0	1047	-	-7,4%
3	4	117	222,0	36,9	29,7	7,5	8,1	1066	54,0	74,0	Dirty	9,0	1047	-	-7,1%
3	4	118	209,3	35,2	27,7	7,6	8,2	1062	39,0	73,0	Dirty	9,0	1047	-	-13,7%
3	1	122	227,7	36,9	29,3	7,8	8,4	1089	52,0	73,0	Clean	9,5	1079	5823	-4,5%
3	1	123	225,2	36,9	29,5	7,6	8,3	1089	52,0	73,0	Clean	9,5	1079	5823	-5,6%
3	1	124	226,3	36,9	29,2	7,8	8,4	1089	52,0	73,0	Clean	9,5	1079	5823	-5,1%
3	4	125	226,1	36,9	29,1	7,8	8,5	1100	57,0	72,0	Clean	9,9	1098	5822	-5,2%
3	4	126	228,3	36,9	29,3	7,8	8,6	1100	57,0	72,0	Clean	9,9	1098	5822	-4,2%
3	4	127	225,5	36,8	29,0	7,8	8,5	1100	57,0	72,0	Clean	9,9	1098	5822	-5,5%
4	-1	198	190,5	34,4	26,9	7,1	7,8	977	54,0	71,0	Dirty	-	-	-	18,8%
4	-1	199	189,9	34,4	27,3	7,0	7,8	976	54,0	71,0	Dirty	-	-	-	19,1%
4	-1	200	189,9	34,3	26,8	7,1	7,7	972	54,0	72,0	Dirty	-	-	-	19,1%
4	-2	201	190,1	34,4	27,3	7,0	7,7	971	55,0	72,0	Dirty	-	-	-	19,0%
4	-2	202	191,4	34,3	26,9	7,1	7,8	968	55,0	72,0	Dirty	-	-	-	18,5%
4	-2	203	191,4	34,2	26,9	7,1	7,8	963	55,0	72,0	Dirty	-	-	-	18,5%
4	-3	204	189,2	34,4	26,7	7,1	7,7	974	54,0	71,0	Dirty	-	-	-	19,4%
4	-3	205	188,2	34,2	26,6	7,1	7,7	956	54,0	72,0	Dirty	-	-	-	19,8%
4	-3	206	188,4	34,3	26,6	7,1	7,7	941	54,0	72,0	Dirty	-	-	-	19,7%
4	-4	207	191,5	34,2	26,7	7,2	7,8	904	53,0	72,0	Dirty	-	-	-	18,4%
4	-4	208	188,2	34,2	27,4	6,9	7,7	928	53,0	71,0	Dirty	-	-	-	19,8%
4	-4	209	189,4	34,2	26,6	7,1	7,7	934	53,0	72,0	Dirty	-	-	-	19,3%
4	4	210	184,4	33,7	26,5	7,0	7,5	915	54,0	73,0	Dirty	-	-	-	21,4%
4	4	211	183,7	33,7	26,4	7,0	7,5	911	54,0	72,0	Dirty	-	-	-	21,8%
4	4	212	183,9	33,7	26,4	7,0	7,5	908	54,0	72,0	Dirty	-	-	-	21,7%
4	3	213	184,5	33,8	26,5	7,0	7,6	909	55,0	72,0	Dirty	-	-	-	21,4%
4	3	214	184,6	33,8	26,5	7,0	7,6	907	55,0	72,0	Dirty	-	-	-	21,4%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Impp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
4	3	215	185,5	33,9	26,6	7,0	7,6	911	55,0	72,0	Dirty	-	-	-	21,0%
4	2	216	185,5	33,7	26,1	7,1	7,7	911	54,0	71,0	Dirty	-	-	-	21,0%
4	2	217	185,1	33,7	26,5	7,0	7,7	910	54,0	72,0	Dirty	-	-	-	21,2%
4	2	218	185,2	33,7	26,5	7,0	7,7	908	54,0	71,0	Dirty	-	-	-	21,1%
4	1	219	185,0	33,9	26,5	7,0	7,7	907	53,0	71,0	Dirty	-	-	-	21,2%
4	1	220	184,6	33,7	26,4	7,0	7,7	905	53,0	71,0	Dirty	-	-	-	21,4%
4	1	221	185,5	33,7	26,1	7,1	7,7	904	53,0	71,0	Dirty	-	-	-	21,0%
4	-1	222	194,8	34,3	26,9	7,3	8,0	875	52,0	71,0	Clean	-	-	-	17,0%
4	-1	223	194,1	34,3	27,3	7,1	8,0	879	52,0	71,0	Clean	-	-	-	17,3%
4	-1	224	194,2	34,3	26,8	7,3	8,0	879	52,0	71,0	Clean	-	-	-	17,3%
4	2	225	191,3	34,2	26,5	7,2	7,9	878	52,0	71,0	Clean	-	-	-	18,5%
4	2	226	191,2	34,1	26,5	7,2	7,9	876	52,0	71,0	Clean	-	-	-	18,5%
4	2	227	191,3	34,1	26,5	7,2	7,9	875	52,0	71,0	Clean	-	-	-	18,5%
4	1	228	191,4	34,1	26,5	7,2	8,0	875	52,0	70,0	Clean	-	-	-	18,5%
4	1	229	191,4	34,1	26,5	7,2	7,9	877	52,0	71,0	Clean	-	-	-	18,5%
4	1	230	191,5	34,1	26,1	7,3	8,0	873	52,0	71,0	Clean	-	-	-	18,4%
5	1	128	208,6	36,9	29,0	7,2	7,8	1053	54,5	73,0	Dirty	8,5	1050	941	-14,0%
5	1	129	205,1	36,7	28,6	7,2	7,7	1053	54,5	73,0	Dirty	8,5	1050	941	-16,0%
5	1	130	205,5	36,7	29,1	7,1	7,7	1053	54,5	73,0	Dirty	8,5	1050	941	-15,8%
5	2	131	199,8	36,6	29,0	6,9	7,6	1053	55,0	72,0	Dirty	8,5	1056	942	-19,1%
5	2	132	200,4	36,6	28,6	7,0	7,6	1053	55,0	72,0	Dirty	8,5	1056	942	-18,7%
5	2	133	201,7	36,7	28,8	7,0	7,6	1053	55,0	72,0	Dirty	8,5	1056	942	-18,0%
5	3	134	209,6	37,0	29,3	7,2	7,8	1066	53,0	73,0	Dirty	8,5	1062	943	-13,5%
5	3	135	208,6	36,9	29,2	7,1	7,8	1066	53,0	73,0	Dirty	8,5	1062	943	-14,1%
5	3	136	209,9	36,9	29,4	7,2	7,8	1066	53,0	73,0	Dirty	8,5	1062	943	-13,4%
5	4	137	212,2	37,0	29,5	7,2	7,8	1065	51,0	73,0	Dirty	8,7	1071	944	-12,1%
5	4	138	212,8	37,1	29,6	7,2	7,8	1065	51,0	74,0	Dirty	8,7	1071	944	-11,8%
5	4	139	212,9	37,2	29,6	7,2	7,8	1065	51,0	73,0	Dirty	8,7	1071	944	-11,7%
5	4	140	227,0	37,4	29,9	7,6	8,3	1054	53,0	73,0	Clean	9,2	1160	944	-4,8%
5	4	141	226,7	37,3	29,4	7,7	8,3	1054	53,0	73,0	Clean	9,2	1160	944	-5,0%
5	4	142	226,4	37,3	29,8	7,6	8,3	1054	53,0	73,0	Clean	9,2	1160	944	-5,1%
5	1	143	220,3	37,0	29,0	7,6	8,3	1062	55,5	72,0	Clean	9,2	1059,0	941	-8,0%
5	1	144	220,7	37,0	29,5	7,5	8,3	1062	55,5	72,0	Clean	9,2	1059,0	941	-7,8%
5	1	145	221,1	37,1	29,1	7,6	8,2	1062	55,5	72,0	Clean	9,2	1059,0	941	-7,6%
6	-1	1	195,2	36,1	28,1	7,0	7,9	1087,0	56,0	69,0	Soiling	-	-	-	-16,4%
6	-1	2	194,1	36,1	28,4	6,8	7,8	1087,0	56,0	68,0	Soiling	-	-	-	-17,1%
6	-1	3	193,1	35,9	27,8	7,0	7,8	1089,0	54,0	69,0	Soiling	-	-	-	-17,7%
6	-4	4	200,7	35,5	28,3	7,1	7,7	1079,0	53,0	74,0	Soiling	-	-	-	-13,1%
6	-4	5	200,0	35,5	28,3	7,1	7,6	1082,0	53,0	74,0	Soiling	-	-	-	-13,5%
6	-4	6	200,1	35,6	28,3	7,1	7,6	1082,0	53,0	74,0	Soiling	-	-	-	-13,4%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Impp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
6	-5	7	198,8	35,3	28,0	7,1	7,6	1074,0	54,0	74,0	Soiling	-	-	-	-14,2%
6	-5	8	195,4	35,3	28,0	7,0	7,5	1090,0	54,0	74,0	Soiling	-	-	-	-16,3%
6	-5	9	195,5	35,3	28,0	7,0	7,5	1093,0	54,0	74,0	Soiling	-	-	-	-16,2%
6	3	10	198,5	35,1	27,8	7,1	7,6	1065,0	54,0	75,0	Soiling	-	-	-	-14,3%
6	3	11	198,4	35,1	27,7	7,2	7,6	1062,0	54,0	74,0	Soiling	-	-	-	-14,4%
6	3	12	199,4	35,3	27,8	7,2	7,6	1062,0	54,0	74,0	Soiling	-	-	-	-13,8%
6	2	13	203,6	35,5	28,8	7,1	7,7	1064,0	53,0	75,0	Soiling	-	-	-	-11,4%
6	2	14	203,3	35,5	28,3	7,2	7,7	1067,0	53,0	74,0	Soiling	-	-	-	-11,5%
6	2	15	202,3	35,4	28,2	7,2	7,7	1068,0	53,0	75,0	Soiling	-	-	-	-12,1%
6	1	16	195,9	35,6	27,7	7,1	7,7	1048,0	53,0	71,0	Soiling	-	-	-	-15,9%
6	1	17	195,6	35,7	27,6	7,1	7,7	1046,0	53,0	71,0	Soiling	-	-	-	-16,1%
6	1	18	195,7	35,7	27,6	7,1	7,7	1045,0	53,0	71,0	Soiling	-	-	-	-16,0%
6	-4	19	207,3	35,7	28,7	7,2	7,8	1070,0	50,0	74,0	Clean	-	-	-	-14,0%
6	-4	20	207,7	35,7	28,6	7,3	7,8	1061,0	50,0	74,0	Clean	-	-	-	-13,8%
6	-4	21	207,4	35,6	28,5	7,3	7,9	1058,0	50,0	74,0	Clean	-	-	-	-13,9%
6	-5	22	208,0	35,5	28,4	7,3	7,9	1052,0	50,0	74,0	Clean	-	-	-	-13,6%
6	-5	23	207,8	35,5	28,0	7,4	7,9	1054,0	50,0	74,0	Clean	-	-	-	-13,7%
6	-5	24	207,6	35,5	28,0	7,4	8,0	1056,0	50,0	74,0	Clean	-	-	-	-13,8%
7	1	163	193,8	35,4	28,2	6,9	7,3	1051,0	54,0	75,0	Dirty	7,9	1020,0	5832	-22,8%
7	2	164	206,0	35,3	29,0	7,1	7,5	1011,0	52,0	78,0	Dirty	-	-	5834	-15,5%
7	2	166	205,0	36,2	29,0	7,1	7,7	929,0	46,0	74,0	Dirty	-	-	5834	-16,0%
7	2	167	201,3	35,9	28,7	7,0	7,6	929,0	46,0	73,0	Dirty	-	-	5834	-18,2%
8	1	147	187,0	35,0	26,8	7,0	7,6	1069,0	54,3	70,0	Dirty	-	-	-	-37,8%
8	1	148	180,4	34,9	27,0	6,7	7,3	1069,0	54,3	71,0	Dirty	-	-	-	-37,9%
8	1	149	182,3	34,9	27,2	6,7	7,4	1069	54,3	70,0	Dirty	-	-	-	-37,9%
8	2	150	194,2	35,1	27,1	7,2	7,9	1044	53,8	71,0	Dirty	-	-	-	-35,1%
8	2	151	197,9	35,2	27,1	7,3	8,0	1044	53,8	71,0	Dirty	-	-	-	-34,5%
8	2	152	194,9	35,1	27,2	7,2	7,9	1044	53,8	70,0	Dirty	-	-	-	-34,2%
8	3	153	194,7	35,1	26,9	7,2	7,9	1055	52,7	70,0	Dirty	-	-	-	-39,8%
8	3	154	197,6	35,1	27,2	7,3	7,9	1055	52,7	71,0	Dirty	-	-	-	-40,0%
8	3	155	200,2	35,3	27,5	7,3	8,0	1055	52,7	71,0	Dirty	-	-	-	-39,7%
8	1	156	199,4	35,1	27,0	7,4	7,9	1078	53,2	72,0	Clean	-	-	-	-25,7%
8	1	157	194,3	35,1	26,9	7,2	7,8	1078	53,2	71,0	Clean	-	-	-	-25,1%
8	1	158	202,2	35,1	27,3	7,4	8,1	1078	53,2	71,0	Clean	-	-	-	-25,5%
8	2	159	201,3	35,3	27,9	7,2	8,0	1115	52,5	71,0	Clean	-	-	-	-45,3%
8	2	160	198,6	35,3	27,6	7,2	7,8	1115	52,5	72,0	Clean	-	-	-	-45,3%
8	2	161	199,3	35,2	27,2	7,3	8,0	1115	52,5	71,0	Clean	-	-	-	-45,9%
9	1	41	190,8	35,6	27,3	7,0	7,5	910	46	72	Soiling	-	-	83	-8,2%
9	1	42	190,7	35,4	27,3	7,0	7,6	1018	47	71	Soiling	-	-	84	-8,2%
9	2	43	192,6	35,2	27,0	7,1	7,7	931	47	71	Soiling	-	-	88	-9,1%

Site	Module No.	Meas. No.	Pmax (P)	Voc (V)	Vmpp (V)	Impp (A)	Isc (A)	Irr. (W/m²)	Module Temp. (°C)	FF	Status	Isc (A)	Irradiation (W/m²)	EL Pic. No.	ΔP from Min. Expected
9	2	44	194,6	35,3	27,5	7,1	7,9	1005	48	70	Soiling	-	-	-	-7,9%
9	1	45	199,5	35,7	27,8	7,2	7,8	993	48	71	Clean	-	-	-	-9,0%
9	1	46	204,2	35,7	27,9	7,3	8,0	965	48	71	Clean	-	-	-	-6,4%
9	1	48	204,1	35,6	27,5	7,4	8,1	987	45	71	Clean	-	-	-	-6,5%
9	2	49	200,9	35,5	27,7	7,3	8,0	1036	45	70	Clean	-	-	-	-8,2%
9	2	50	201,9	35,5	27,0	7,5	8,0	1042	45	71	Clean	-	-	-	-7,6%
9	2	51	200,0	35,5	27,2	7,4	8,0	1035	45	71	Clean	-	-	-	-8,7%
10	1	25	191,2	35,7	27,1	7,1	7,8	1091	53	69	Soiling	-	-	-	-9,5%
10	1	26	190,7	35,7	26,7	7,1	7,7	1100	53	69	Soiling	-	-	-	-9,8%
10	1	27	190,4	35,6	26,8	7,1	7,7	1104	53	69	Soiling	-	-	-	-9,9%
10	2	28	184,5	35,0	25,8	7,1	7,7	1114	52	69	Soiling	-	-	-	-13,5%
10	2	29	183,9	35,1	26,3	7,0	7,6	1117	52	69	Soiling	-	-	-	-13,9%
10	3	30	184,6	35,7	27,2	6,8	7,7	1066	50	68	Soiling	-	-	-	-13,5%
10	3	31	187,8	35,7	27,5	6,8	7,7	942	50	68	Soiling	-	-	-	-11,5%
10	1	32	160,2	35,3	27,0	5,9	7,6	971	49	60	Soiling	-	-	-	-31,2%
10	1	33	170,9	35,5	26,6	6,4	7,7	960	49	63	Soiling	-	-	-	-22,8%
10	1	34	171,7	35,4	26,7	6,4	7,7	952	49	63	Soiling	-	-	-	-22,2%
10	1	35	169,8	35,4	26,5	6,4	7,7	947	49	62	Soiling	-	-	-	-23,6%
10	2	36	192,5	35,6	26,8	7,2	7,9	1101	50	68	Clean	-	-	-	-11,5%
10	2	37	191,0	35,5	26,4	7,2	7,7	1133	50	70	Clean	-	-	-	-12,3%
10	2	38	189,1	35,4	26,6	7,1	7,7	1158	50	69	Clean	-	-	-	-13,5%
10	2	39	187,5	35,2	26,3	7,1	7,8	1149	51	69	Clean	-	-	-	-14,5%
10	2	40	187,9	35,1	26,3	7,2	7,8	1145	51	68	Clean	-	-	-	-14,2%

Annex II – Documentation required from the Rooftop Owners

Required Documents		Description	Available		Comments Owner
			yes	no	
1	**GENERAL ASPECTS**				
1.1	Customer name				
2	**RELEVANT DOCUMENTS DURING THE DEVELOPMENT PHASE**				
2.1	Yield assessment				
3	CONTRACTS				
3.1	O&M contract				
3.2	EPC contract				
4	**COMPONENTS**				
4.1	PV Module				
4.1.1	Amount of modules				
4.1.2	Datasheet				
4.1.3	Warranty documentation				
4.1.4	Flash-lists				
4.2	Mounting structure				
4.2.1	Technical description				
4.2.2	Sectional drawings of the module-tables/structure				
4.3	Inverter				
4.3.1	Amount of inverters				
4.3.2	Warranty documentation				
4.3.3	Datasheet				
4.4	Combiner boxes				
4.4.1	Drawings				
4.4.1	Datasheets				
4.5	Monitoring system (SCADA)				
4.5.1	Remote access to SCADA system				
4.5.2	Datasheets of the weather sensors				
5	**DESIGN**				
5.1	Exact module and inverter location (if possible as CAD drawings as well)				
5.2	Location of combiner boxes in the field				
5.3	Number of strings				
5.4	Single line diagram				
6	**INSTALLATION**				
6.1	Installation date and grid connection date				
6.2	Location of the installed sensors				
6.3	As-built layout				
7	**COMMISSIONING**				
7.1	Commissioning protocols				
8	**PERFORMANCE**				
8.1	Internal or external reports				
8.2	Irradiation and temperature data on hourly basis since COD				
9	**O&M**				
9.1	Monthly operating reports or any other information collected since COD regarding the operational status of the plant				
9.2	Procedures for verifying correct system operation				
9.3	Preventive maintenance checklists				
9.4	Cleaning procedure				

Annex III – TDD Checklist

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
0	**General**					
0.1	Date of inspection					
0.2	Name and size of the plant					
0.3	Coordinates					
0.4	Commercial Operation Date (COD)					
0.5	Name of the Owner					
0.6	Name of the EPC					
0.7	Name of the O&M company					
1	**Contracts**					
1.1	Warranties of the EPC contract (PAC and FAC)					
1.2	Warranties of the O&M contract					
1.3	Completeness of the PAC in the EPC contract					
1.4	Name of the OE					
1.5	Name of the LTA					
2	**PV Plant Design**					
2.1	DC size					
2.2	AC size					
2.3	DC/AC ratio					
2.4	Level of injection					
2.5	Size of each PCU					
2.6	Module type					
2.7	Module technology					
2.8	Inverter type					
2.9	Pitch					
2.10	Tilt of the modules					
2.11	Mounting structure type					
2.12	Module arrangement					
2.13	Statics					
2.14	Location of the inverters and AC distribution boxes					
3	**Electromechanical Installation**					
3.1	**Mounting structure**					
3.1.1	Module fixation					
3.1.2	Labelling of rows					
3.1.3	Rust mounting structure					
3.2	**Combiner box (CB)**					
3.2.1	Sealing of the cable glands					
3.2.2	Cleanliness of the CB					
3.2.3	Overvoltage in the CB					
3.2.4	Labelling of the CB					
3.3	**Cables**					
3.3.1	Cable damage					
3.3.2	Labelling of cables					
3.3.3	Connectors					
3.3.4	Cable fixation					
3.3.5	Bending radius					
3.3.6	Protection of cables against UV					
3.3.7	Sealing of tubes					

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
3.3.8	Cable pipes					
3.4	**Inverter**					
3.4.1	Overvoltage in the inverter					
3.4.2	Cleanliness of the inverter room					
3.4.3	Cooling					
3.4.4	Status of filters					
3.4.5	Entrance of the communication cable					
3.5	**Grounding**					
3.5.1	Status of the grounding and equipotential bonding system					
3.5.2	Functional grounding					
3.6	**Civil work**					
3.6.1	Status of the roads					
3.6.2	Status of the drainage system					
3.7	**Documentation**					
3.7.1	Completeness of the as-built documentation					
3.7.2	Progress reports of the installation phase					
4	**Commissioning**					
4.1	Tests conducted at PAC and FAC?					
4.2	Did anyone witness and validate?					
5	**System Performance**					
5.1	Parallel logging of the irradiation sensors					
5.2	Parallel logging of the temperature sensors					
5.3	Date of calibration of the sensors					
5.4	Weather station status					
5.5	What has been the PR of the plant since grid connection?					
5.6	How is the PR calculated?					
5.7	PR correction					
5.8	Yield assessment					
6	**Module Quality**					
6.1	Visual inspection modules					
6.2	Availability of the flash lists					
6.3	Scratches in back sheet					
6.4	Long term durability certificates of the PV modules and inverters					
6.5	IR analysis					
6.6	EL analysis					
6.7	IV curve tracing					
6.8	Snail trails					
6.9	PID					
7	**Operation & Maintenance**					
7.1	Specific issues reported since COD					
7.2	Relevant environmental events					
7.3	Experience of workers in PV					
7.4	Experience of workers in O&M					
7.5	H&S program					
7.6	Allowance to operate MV devices					

No.	Item	Interview needed?	Photo needed?	Comments	Photo No.	Note No.
7.7	Calculation of the soiling loss					
7.8	Cleaning methodology					
7.9	Vegetation					
7.10	Check the tools and devices used					
7.11	Reporting					
7.12	Reaction times					
7.13	Preventive maintenance					
7.14	Corrective maintenance					
7.15	Availability calculation					
7.16	Responsibility for SCADA					
7.17	SCADA resolution					
7.18	Theft on site					
7.19	Curtailment and grid stability					
7.20	Reactive power compensation and power quality requirements					

Annex IV – Measurement Equipment used on Site

I- HT SOLAR-IV [S/N 11110683, calibration date 28.05.2019, tolerance 5%]

II- HT SOLAR-IV [S/N 11011124, calibration date 05.12.2019, tolerance 5%]

HT Solar-IV is a peak power measuring device and IV curve tracer that provides the measurement of the IV curve of photovoltaic modules and strings on site. Measurements of PV array IV characteristics under actual on-site conditions and their extrapolation to Standard Test Conditions (STC) can provide data on power rating, verification of installed array power performance relative to design specification, detection of possible differences between on-site module characteristics and laboratory or factory measurements, and detection of a possible performance degradation of module and arrays with respect to on-site initial data.

Figure 106: HT SOLAR-IV IV curve tracer [source: pv-engineering]

I- Irradiation sensor HT304N [S/N 14042952, calibration date 02.2019, tolerance <3%]

II- Irradiation sensor HT304N [S/N 14032936, calibration date 01.2019, tolerance <3%]

HT304N is a reference cell for sun irradiation measurements that enables a precise analysis of PV module power or energy yields using measured values from the sensor. It has a double input for connection to mono or multi crystalline modules.

Figure 137: Duo reference cell [source: PI Berlin]

I- Infrared camera Testo T885 [S/N 02298789, calibration date 01.03.2019, tolerance <2°],

II- Infrared camera Testo T885 [S/N 02732076, calibration date 01.03.2019, tolerance <2°]

Testo T885 enables non-destructive diagnosis of some thermal and electrical failures in PV modules. It provides fast, real-time, two-dimensional infrared (IR) imaging, revealing characteristic features of PV systems. The measurements can be performed during normal operation for individual PV modules as well as large arrays.

Figure 138: Infrared camera [source: Testo]

Through the Sony ILCE-7S camera with a CCD High pass edge filter, electroluminescence pictures are taken in the field to reveal failures such as microcracks, PID, failure of diodes or similar, as a complement to the STC-measurement and infrared inspection. EL imaging is particularly suitable for the detection and tracking of crack-related issues, which can occur for example during module transportation or installation.

Figure 139: SONY ILCE-7S with CCD high pass edge filter [source: PI Berlin]

Annex V – Normative References Used for the Study

IEC 61557-4:2007	**Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. – Equipment for testing, measuring or monitoring of protective measures Part 4: Resistance of earth connection and equipotential bonding**
IEC 60664-1:2007	Insulation coordination for equipment within low-voltage systems Part 1: Principles, requirements and tests
IEC 61215:2005	Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval
IEC 61730-1&2:2005	Photovoltaic (PV) module safety qualification
IEC 61829:2015	Photovoltaic (PV) array - On-site measurement of current-voltage characteristics
IEC 60364-4-41:2005	Low-voltage electrical installations - Part 4-41: Protection for safety - Protection against electric shock
IEC 60364-4-42:2010	Low-voltage electrical installations - Part 4-42: Protection for safety - Protection against thermal effects
IEC 60364-4-43:2008	Low-voltage electrical installations - Part 4-43: Protection for safety - Protection against overcurrent
IEC 60364-4-46:1981	Electrical installations of buildings. Part 4: Protection for safety. Chapter 46: Isolation and switching
IEC 60364-5-51:2005	Electrical installations of buildings - Part 5-51: Selection and erection of electrical equipment - Common rules
IEC 60364-5-52:2009	Low-voltage electrical installations - Part 5-52: Selection and erection of electrical equipment - Wiring systems
IEC 60364-5-54:2011	Low-voltage electrical installations - Part 5-54: Selection and erection of electrical equipment - Earthing arrangements and protective conductors
IEC 60364-6:2006	Low-voltage electrical installations - Part 6: Verification
IEC 60364-7-712:2011	Electrical installations of buildings - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems
IEC 60529 1989+A1:1999+A2:2013	Degrees of protection provided by enclosures (IP Code)
IEC 60068-2-68:1997	Environmental testing - Part 2: Tests; test L: Dust and sand
IEC 60721 1-2:2013	Classification of environmental conditions
IEC 60721 3-4:1995	Classification of environmental conditions - Part 3: Classification of groups of environmental parameters and their severities - Section 4: Stationary use at non-weather protected locations (?)
IEC 61084-1:1991	Cable trunking and ducting systems for electrical installations
IEC 61238-1:2003	Foundation earth electrode - Planning, execution and documentation
IEC 62446:2009	Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance
IEC 62548:2010	Photovoltaic (PV) arrays - Design requirements
UL 1703:2002	Standard for Flat-Plate Photovoltaic Modules and Panels
VDE-AR-E-2283-4:2010-10	Requirements for cables for PV systems
2 PfG 1169/08.2007*	Requirements for cables for use in photovoltaic-systems